THE QUATERNARY ICE AGE

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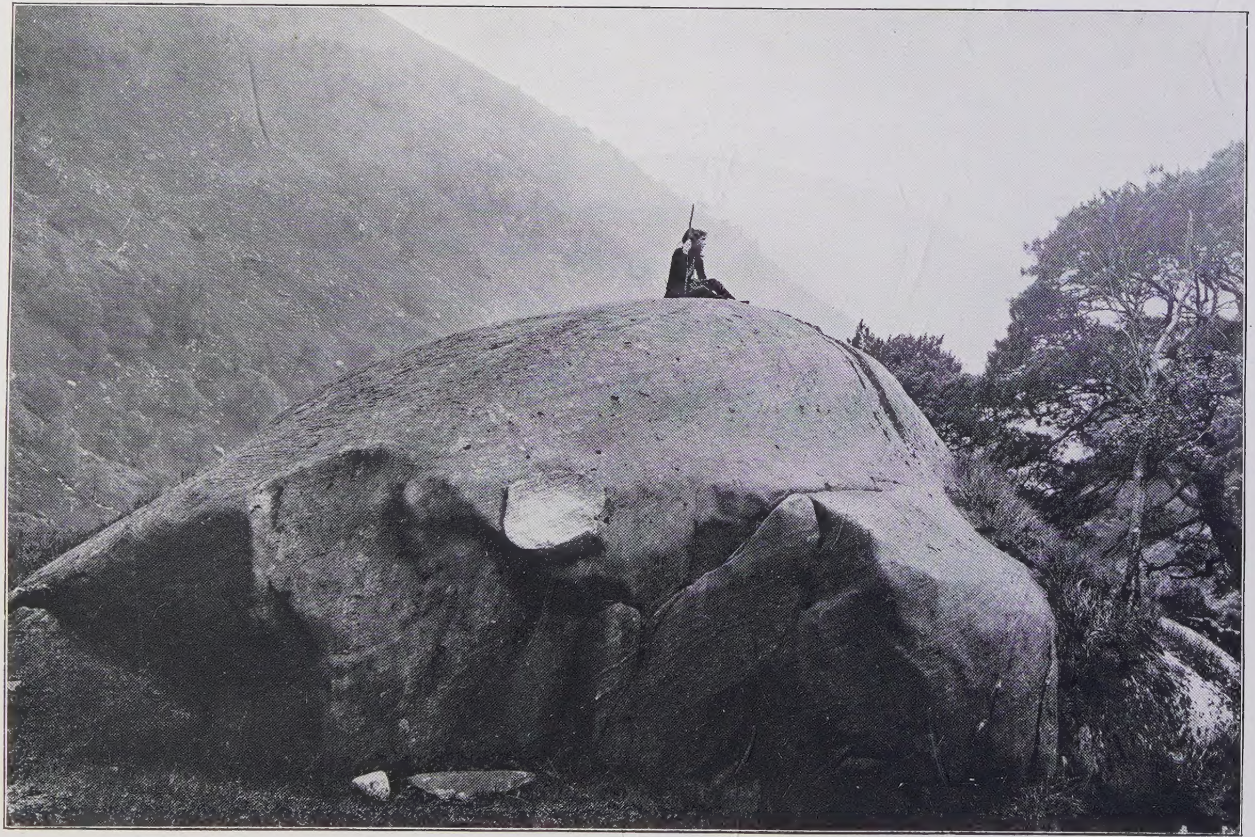
PLATE I.



ROCHE MOUTONNÉE ON THE ROADSIDE NEAR MAM BEAG, GLEN NEVIS, SCOTLAND.

Viewed obliquely from the stoss end.

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland.

Frontispiece.

THE QUATERNARY ICE AGE

BY

W. B. WRIGHT

OF THE GEOLOGICAL SURVEY OF IRELAND

MACMILLAN AND CO., LIMITED
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1914

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TO THE MEMORY OF

T. F. JAMIESON

OF ELLON

ORIGINATOR OF THE ISOSTATIC THEORY

OF THE QUATERNARY OSCILLATIONS OF SEA-LEVEL

PREFACE

THE study of Glacial Geology has of late years made such strides that it is no easy matter to keep abreast of recent developments. Much of the literature of the subject is scattered through foreign publications for the most part unknown except to the specialist and always difficult of access. It is, moreover, an immense literature, and though the papers of outstanding importance are relatively few, their discovery necessarily entails much unprofitable reading in foreign languages. There is no general work in English which might serve as a guide to this literature, or enable the geologist who is interested in glacial subjects to obtain a grasp of the leading features of the subject. The following pages were originally designed to supply this want, but much has crept in, in the way of reasoning and speculation, which is entirely my own. I am afraid such personal colouring is unavoidable, and I am sure any attempt to avoid it would have resulted in the book being quite unreadable. I think, however, I have stated things in such a manner as to make it clear to the reader when, and to what extent, he is being led away from the groundwork of solid fact which forms the greater bulk of the work.

It is in the chapter dealing with the isostatic theory that I have been most daring in the introduction of new ideas. I have endeavoured to show that the complicated earth movements which have in the past been commonly invoked to explain the late-glacial and post-glacial changes of level in Scandinavia are not at all necessary, and that all the observed phenomena may be accounted for in the simplest manner by unchecked isostatic recovery from the effects of the ice-load combined with a single oscillation of the sea-level. I have also attempted to apply this theory to the analogous isostatic areas in Great Britain and North America, and have pointed out to what extent there is agreement or discrepancy. This theoretical discussion has, however, been confined to a special chapter, and an endeavour has been made to phrase the actual description of these phenomena in such a manner as not in any way to beg the question.

The preparation of this volume has extended over many years, and it is difficult for me to acknowledge all the help I have received from various sources. As regards the illustrations, I am indebted to Mr. Cantrill and other officers of the English Geological Survey for assistance in preparing the map of the glaciation of the British Isles on p. 49. For the use of photographs, many of which are hitherto unpublished, I have especially to thank Mr. Godfrey Bingley, Professor Högbom, Professor Swain, and the Geological Survey of Scotland. For the illustration of the chapter on Quaternary Man I have largely availed myself of the figures in Professor Sollas's *Ancient Hunters*, and Professor De Geer has been kind enough to supply me with the original drawings of the illustrations to his famous paper on the laminated clays of Sweden.

W. B. WRIGHT.

DUBLIN, 1914.

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CHAPTER I

GLACIERS AND ICE-SHEETS

Mountain glaciers and ice-sheets—The physics of ice motion—Characteristics of mountain glaciers—Surface and end-moraines—Ablation—Outwash gravels—Effect of a glacier terminating in water—Classification of mountain glaciers—The snow-slope—Its erosive action—Solifluction—The corrie glacier—The excavation of corries—The valley glacier—Hanging valleys—The expanded foot glacier—The Piedmont glacier—The glacial sculpture of mountain ranges—Present day ice-sheets and ice-caps—The Greenland Ice-sheet—Its physics and meteorology—The Antarctic Ice-sheet.

THE apparent transgression of the law of uniformity involved in many of the fundamental conceptions of Glacial Geology is at the root of much of the impermeability to new ideas exhibited by certain members of the geological hierarchy during the last twenty or thirty years. As long as the diminutive Alpine glaciers were the only well-known working models of the action of land ice, it required an elastic and original mind like that of Agassiz to bridge the gap between what had actually been seen happening and what was conceived to have taken place in the Quaternary Period. At the present day, however, there is no excuse for any scepticism regarding the importance of ice as a geological agent. The progress of arctic exploration has of recent years been so rapid, and the explorers themselves so keenly alive to the importance of scientific observation, that we now possess a wealth of information concerning glaciers and ice-sheets immensely larger than any in the Alps, and quite comparable with those which at one time covered the continents of Europe and North America. The phenomena of the Ice Age, instead of transcending all experience, are thus to be regarded as the last and most striking example of Lyell's great principle that the agencies which fashioned the earth throughout the geological ages are such as can be seen in action in various parts of the world at the present day.

Mountain glaciers and ice-sheets.

In his recent classification of existing glaciers Hobbs[1] distinguishes no less than fifteen different types and sub-types. Many of these, however, grade into one another, and the distinctions between the different classes are mostly of minor importance. It will conduce to greater clearness to emphasise here the essential distinction between mountain glaciers and ice-sheets. In the physics of their nourishment and depletion, and above all in their physiographical and geological effects, these two types of ice accumulation exhibit fundamental differences. It might almost be said that they have little in common except the possession of a pseudo-plastic motion under the action of gravity, which is the property of all ice masses great and small.

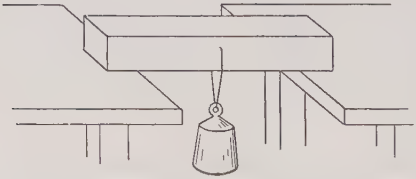

FIG. 1.—Diagram of experiment to show the effect of regelation.

Apparent plasticity of ice.

Regelation.

As the apparent plasticity of ice is the first cause of all glacial action, it will be necessary to enquire more closely how it comes to have such a property. We know it is a crystalline body, and therefore cannot be plastic in the true sense of the word. The two terms are essentially contradictory. The explanation, however, lies in the peculiar phenomenon of regelation. Most people nowadays will have either seen or read of the striking experiment of passing a wire round a block of ice and attaching thereto a heavy weight. In the course of time the wire cuts completely through the ice, but without dividing it into two portions. When subjected to a great enough pressure ice possesses the property of becoming temporarily fluid, freezing again immediately the pressure is relaxed. The ice in contact with the bottom of the wire melts under the influence of the pressure, slips round to the top, and then at once freezes again, so that the wire actually cuts through the mass without leaving any trace of its passage. This property is more scientifically expressed by saying that pressure lowers the melting point of ice, and if the melting point becomes lower than the temperature of the ice the latter must begin to melt. Now glacier ice is granular, each granule consisting of a crystal or group of crystals. If the mass be subjected to deforming forces it is clear that at certain portions of the contact between the grains the pressure must increase until melting takes place, and a film of water slips away into a position of less pressure and there refreezes. The repetition of this process enables the grains to change their shapes and move over one another with relative ease. In this manner there is produced in large masses of ice an effect equivalent to plastic flow, but in its inner mechanism really essentially different.

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[1] Hobbs, *Characteristics of Existing Glaciers*, p. 41 (New York, 1911).

Granular nature of glacier-ice.

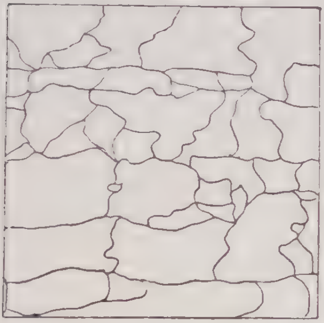

FIG. 2.—Vertical section of glacier-ice cut parallel to the direction of flow, to show the granular character. (After Deeley.)

Supposed limit to thickness of an ice-sheet.

This property of melting under pressure has led certain geologists, who really ought to know better, into the error of supposing that there exists a limit to the thickness which may be attained by an ice-sheet or glacier. They argue that when the thickness is sufficiently great to lower the melting point to the temperature of the basal layers any further growth on the upper surface will be compensated by melting at the base until equilibrium is re-established. The fallacy arises from failure to take into consideration the enormous latent heat of water. Before one gramme of ice in these basal layers can turn into water, it must obtain sufficient heat to lower 80 grammes of water 1° centigrade. It can only get this heat from the adjoining ice, which is thus immediately reduced below the newly established melting point. It is therefore clear that the basal melting which results from increase in thickness is absolutely negligible in comparison to that increase, so that under sufficiently favourable conditions there is no limit to the thickness of an ice-sheet. It is hardly necessary to point out that, in the above described process of melting and regelation around the surfaces of the granules, in virtue of which glacier ice possesses its pseudo-plasticity, no such difficulty arises, since the latent heat absorbed in melting at one side of the granule is at once liberated on refreezing at the other side.

The mountain glacier.

The most important distinction between the mountain glacier and the ice-sheet is the presence of mountain slopes dominating the former. A mountain glacier occupies a hollow or valley among mountains, the upper slopes of which rise high above its surface. It is fed from the snow-fields in the interior of the mountains or on the upper slopes of the valley. These snow-fields are generally known as the firn or névé. The glacier itself is merely a stream of transparent granular ice more or less charged, especially in its lower layers, with rock debris and mud. It moves slowly down the valley, the velocity varying from a few feet per day in the case of some glaciers to as much as 100 feet in others. The motion is more rapid in the centre of the glacier than at the sides, and the effect of this inequality is seen in numerous vertical cracks or crevasses pointing up stream at an angle of 45° to the valley wall. Where the glacier descends over a step in the valley floor an ice-fall is produced which is generally marked by a profusion of tumbled blocks and pinnacles of ice known as séracs. Owing to the descent of rock fragments from overhanging slopes the surface of the ice is frequently covered with debris and strewn with great boulders. The motion of the ice streaks these out in lines stretching away from the point of supply. Where two ice flows meet around a projecting knob there is almost always a line of surface debris stretching away down stream from the point of confluence. When this rock debris reaches the termination of the glacier it is shovelled off and formed into end-moraine which, if the glacier front remain stationary for a sufficiently long period, takes the form of a ridge stretching across the valley.

Subglacial waters.

The active melting which goes on in the lower reaches of most glaciers gives rise to streams of all sizes which flow on the surface until they plunge into crevasses. Their subsequent course is through the innumerable tunnels with which the lower layers of the ice are honeycombed. The velocity of flow in these tunnels must often be very great owing to their confined nature and the head of water behind. Their transporting and grinding power is thus much greater than that of surface streams. This accounts for the well-worn character of the outwash gravels and the large boulders often found embedded in or even forming a considerable portion of them. When the sub-glacial streams emerge along the glacier front their velocity is checked owing to the removal of the hydrostatic pressure, and the debris borne along by them is at once deposited and spread out as a huge fan, commonly known as the outwash apron. The courses of the streams across this apron of sand and gravel are very erratic and subject to incessant change. They frequently split up into innumerable minor water-courses which unite again with one another or with other water-courses. The streams never settle into any proper bed, but wander incessantly on the surface of the fan, levelling down any inequalities and spreading the material further afield. Great blocks of ice are often embedded in the outwash gravels, and when they melt a hollow is left. In this way arise the pitted plains so often found in connexion with the quaternary glaciation.

Outwash.

Delta and esker formation.

If the glacier happens to terminate in standing water, such as a moraine- or ice-dammed lake, or in the sea, the results are somewhat different. In this case, if the glacier front remains stationary for a sufficient time, a delta is built up to the surface of the water. In the case of a rapidly retreating ice front, however, the delta has not time to form, and each sub-glacial stream heaps up at its mouth a series of mounds which are really half-formed deltas. As the orifice retreats these mounds must form a more or less continuous chain along the line of retreat. This is the process by which the peculiar gravel ridges known as eskers are formed. No esker has, however, been anywhere observed in connexion with a modern glacier. This is, of course, due to the conditions necessary for their production, such as the presence of standing water and the rapid retreat of the ice front, being seldom realised in the case of modern glaciers and also, no doubt, to the difficulty of observation under water. A glacier terminating on land can for obvious reasons never form an esker.

Erosion.

In dealing with the erosive effects of mountain glaciers and the physiographical changes they produce in the ranges where they exist, it is necessary to take into consideration their size and development. The most diminutive type of glacier is merely a snow-slope lying against some steep face of rock. This is often surrounded by a ridge of debris having somewhat the appearance of a moraine, but really formed only of scree which has slid down over the snow from the rocks above. When sufficiently thick a snow-slope begins to assume the character of a true glacier through its lower layers becoming compacted into ice and the whole acquiring a forward motion through the action of gravity. Although such diminutive glaciers have next to no scouring action on the rocks beneath them, yet they are by no means to be ignored as agents of denudation. The daily melting of the snow keeps the rocks around thoroughly soaked with water at zero temperature, so that the action of frost is more than usually effective in

The snow-slope.

Solifluction.

splitting them to pieces. On the gentler slopes where this debris rests it creeps along, and is transported to lower levels by the process of rock-flow known as solifluction. The importance of this type of denudation has only been thoroughly realised of recent years. In crossing Spitzbergen Sir Martin Conway encountered large quantities of this "snow-bog" creeping down into the valley from the hills above. In describing the nature of the surface on one of the gentler slopes he says:

> "The muddy disintegration of the friable rocks above here lies almost flat for a while in its slow, glacier-like descent. Expanding and contracting between extremes of temperature, it becomes cracked up hexagonally. Seeds find lodgment in the cracks, which thus become outlined by ridges of mossy and other increasing vegetable growths. The naked mud within the hexagons again, by processes of freezing and thawing, is forced up into rough and broken domes, whilst the vegetation grows into bosses and clogs the water washing down from snow-beds above. The ground becomes saturated, and a regular bog is formed, which moves slowly downward, sometimes splitting into crevasses, or giving way into stream channels, whilst, at the time of great snow-melting, small mud rivers flow down on to it, and further diversify and confuse the 'soft and tangled surface.' As the ground beneath is released from its winter bondage, the whole becomes softer and less stable. Thus it flows, rather than falls, to the valley below, where it comes to relative repose on the wide and ever-widening boggy flat.
>
> "Farther up the hill-sides one can watch the process whereby the mud is formed out of the soft horizontally-bedded rocks of which the hills are built. Melting snow and splitting frost loosen and crack the slabs into a mere slope of debris, all rotten and ready again to split and resplit. Sodden snow and trickling water rapidly produce immense quantities of mud, which partly support, partly carry down, the stones that are not reduced to powder. On hot or wet days streams of this stuff, small mud avalanches, in which the mud predominates over the stones, trickle down the slopes, and either reform on gentler slopes below, or flow on to the surface of some glacier. In the latter case they are carried down, and ultimately either shovelled off the sides and end to form astonishingly large masses of boulder-clay, or dumped into the stream and carried straight away to fill the estuary at the river's mouth."—Sir Martin Conway in *The First Crossing of Spitzbergen*, p. 128, London, 1897.

The corrie glacier.

When a snow-slope glacier becomes of sufficient magnitude to occupy the whole head of a valley, it becomes a cirque- or corrie-glacier. It is now an agent of the highest importance in the fashioning of mountain ranges. Although the process was until recently never well understood, yet it has long been recognised that such glaciers have a remarkable power of scooping out the valley heads in which they lie. Abandoned cirques and corries are frequently occupied by a lake, sometimes held in behind a crescentic moraine, but often contained in an actual rock basin, and surrounded by precipitous slopes or even perpendicular cliffs. Maxwell Close[1] pointed out in the year 1870 that the formation of the rock basin was easy to understand, since the glacier must have a greater scouring action in its centre than elsewhere, the ice being here thicker and the pressure on the rock bed greater. The recession of the valley slopes, so as ultimately to form almost perpendicular cliffs, went for a long time, however, without explanation. It was not until the year 1899 that light was first thrown on the subject. Then for the first time what appears to be the true explanation was brought forward by Willard D. Johnson,[2] topographer to the United States Geological

Origin of corrie lake basins.

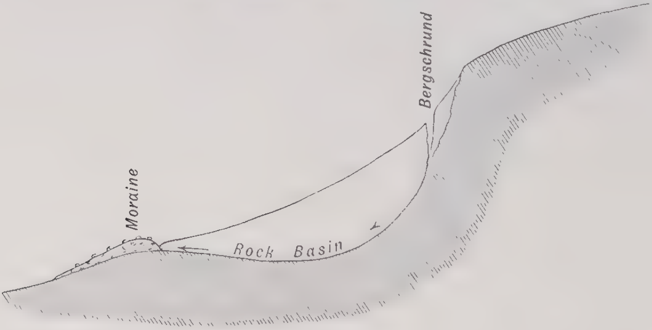

FIG. 3.—Diagrammatic section of a corrie-glacier showing the moraine, the rock basin, and the relation of the bergschrund to the corrie-face.

Origin of the corrie cliffs.

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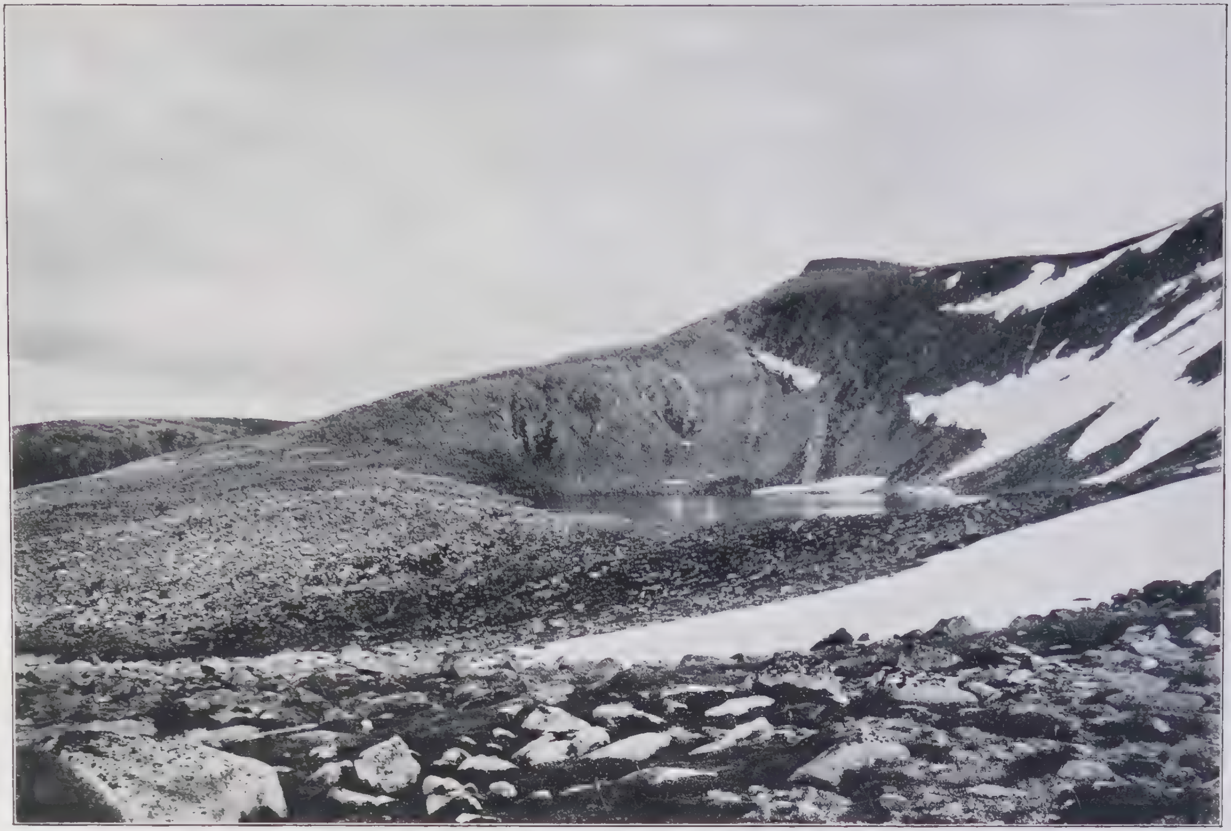
[1] Maxwell Close, "On some Corries and their Rock-Basins in Kerry," *Journ. of the Royal Geol. Soc. of Ireland*, vol. ii. p. 236 (1870).

[2] Willard D. Johnson, "The Profile of Maturity in Alpine Glacial Erosion," *Journal of Geology*, vol. xii. p. 569 (1904).

PLATE II.



COIRE AN LOCHAIN, NEAR BRAERIACH IN THE CAIRNGORMS (SCOTLAND).

A miniature corrie with typical moraine and enclosed lake. Altitude 3267 feet.

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland.

To face p. 8.

Survey. Realising that the ordinary abrading or scouring action of the ice could in no way account for the production of the cliff, he suspected some kind of sapping or plucking action along the contact of the ice with the wall of the corrie. To test this he had himself lowered into the bergschrund, which is a huge crevasse a short distance out from the cirque wall and running parallel to it. At a depth of 150 feet he found that the crevasse reached the rock wall, and for a height of 20 feet one side was actual rock. The rock face, though hard and undecayed, was much riven, the fracture planes outlining sharply angular masses in all stages of displacement and dislodgment. Several blocks were tipped forward and rested against the opposite wall of ice; others, quite removed across the gap, were incorporated in the glacier mass at its base. The continual supply of moisture produced by the daily melting of the snow during summer keeps the crevices of the rocks full of water, and enables the nightly frosts to exert a most powerful disintegrating action. The loose blocks become incorporated in the ice and are carried off by the slow motion of the glacier. The bergschrund becomes filled with snow and closes up during the winter, but on the return of summer it reopens

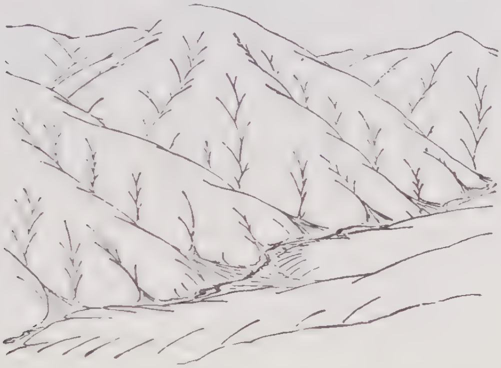


FIG. 4.—Diagram of a mountainous region which has been subjected to normal subærial erosion, the lateral valleys being aggraded to the main valley. (After Davis.)

higher up and nearer to the rock wall, thus facilitating the removal of the incorporated material.

It must not be forgotten that Johnson only proved this disintegrating and plucking action to a depth of 150 feet below the surface of the snow, a very inconsiderable proportion of the whole depth of the corrie face. It is not improbable, however, that the bergschrund may in other places go considerably deeper. There is, moreover, no necessity to consider this action to extend the whole way down the face, for the lower slopes in most abandoned corries are not nearly so precipitous as the upper, and exhibit remarkable ice moulding, as if the intense scouring action which produced the lake basin in the bottom of the corrie had also had no small effect on the lower portion of the walls.

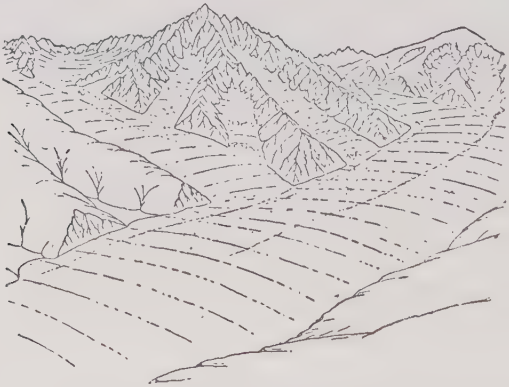
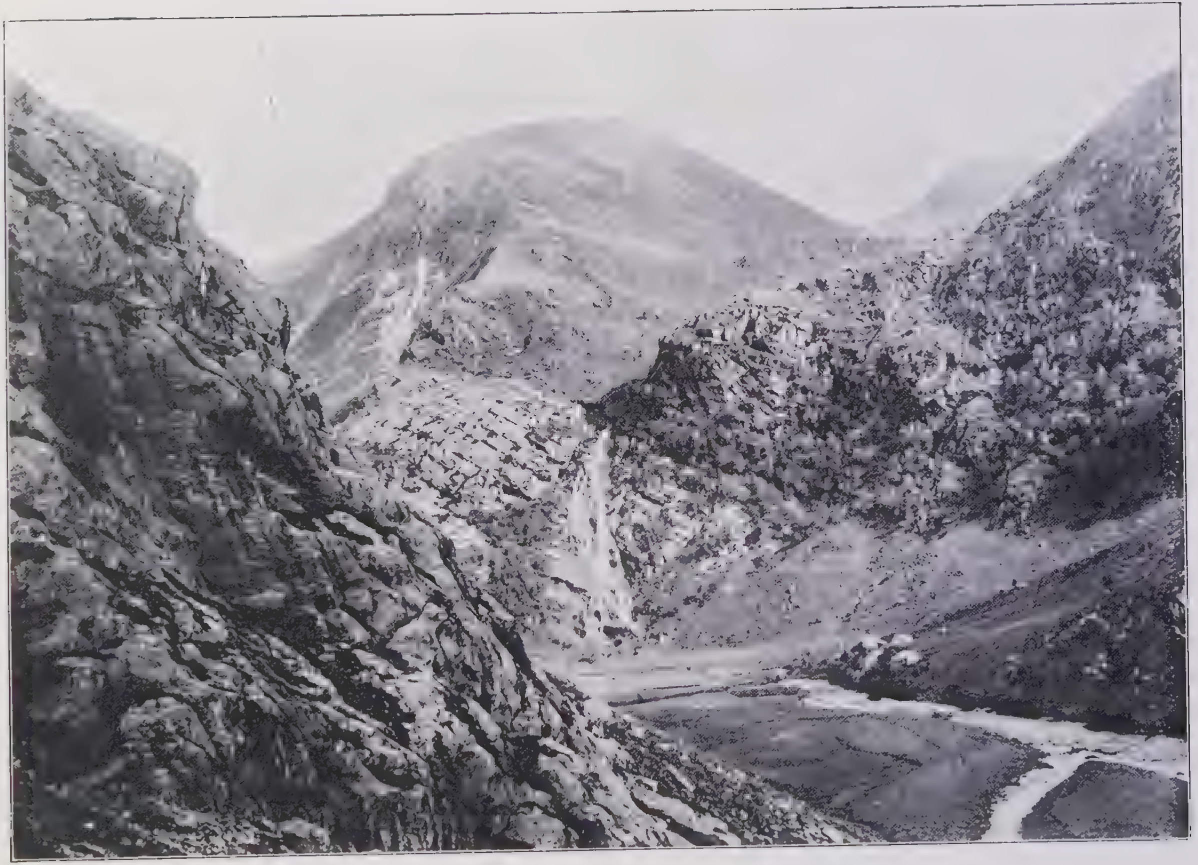


Fig. 5.—The same region after most of the valleys have been occupied by glaciers, and glacial erosion has already reached an advanced stage. (After Davis, from Bowman's *Forest Physiography*.)

The valley glacier.

When a glacier is sufficiently powerful to emerge from the enlarged valley head or corrie where it is nourished, it belongs to the class very properly known as valley glaciers. Several corrie glaciers often unite together to form a single valley glacier. Such a glacier generally widens and deepens the valley along which it flows, forming a U-shaped trough. When the glacier disappears, the effect of this widening and deepening is

PLATE III.



HANGING VALLEY ENTERING THE MAIN VALLEY AT STEALL IN GLEN NEVIS, SCOTLAND.

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland.

To face p. 11.

seen in the lack of accordance between the tributary and main valleys. Their mouths lie high up on the slopes, and the streams descend the sides of the main valley in a series of cascades. These lateral valleys are then referred to as hanging valleys. They may be produced even when the lateral valley nourished a glacier of its own which was tributary to that in the main valley, for, although the surfaces of the two glaciers may be accordant, their floors rarely are, on account of the greater erosive power possessed by the main glacier.

Hanging valleys.

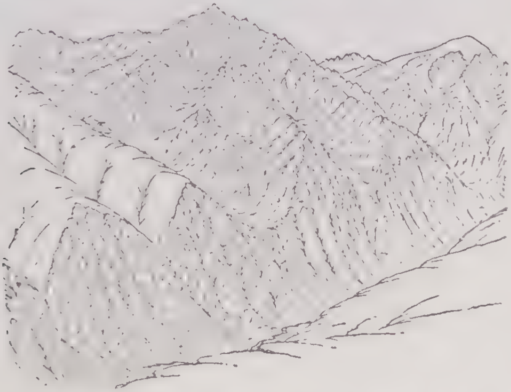


FIG. 6.—The same region after the disappearance of the glaciers. The lateral valleys, both glaciated and unglaciated, now hang to the main valley, and the mountains are excavated to varying extents by corrie formation. (After Davis, from Bowman's *Forest Physiography.*)

When a mountain glacier reaches the mouth of its valley and deploys upon a plain, it is then said to have an expanded foot. The ice forms a more or less semicircular fan upon the plain, and the motion towards the ice front is more or less normal to it. If the glacier remains stationary for long periods, crescentic wreaths of end-moraine are formed, outside which is the outwash apron. When a glacier of this nature retreats, it leaves a central basin in which a lake usually forms. This basin lies partly within the mouth of the valley, but also spreads out on the plain. In some cases it sends out finger-shaped lobes which radiate in every direction from

Expanded foot.

Crescentic terminal moraines.

Lake basin.

Drumlin belt.

The glacier series.

the central basin towards the moraine. The Alpine glaciers of quaternary age left behind them an additional feature in the form of a belt of drumlins, or lenticular hills of ground moraine, between the central basin and the end-moraine, but this feature is not so general as the others. The diagram in Fig. 13, after Penck, shows the ideal glacier series when all four characteristic features, namely, central basin, drumlin belt, end-moraine, and outwash apron are fully developed.

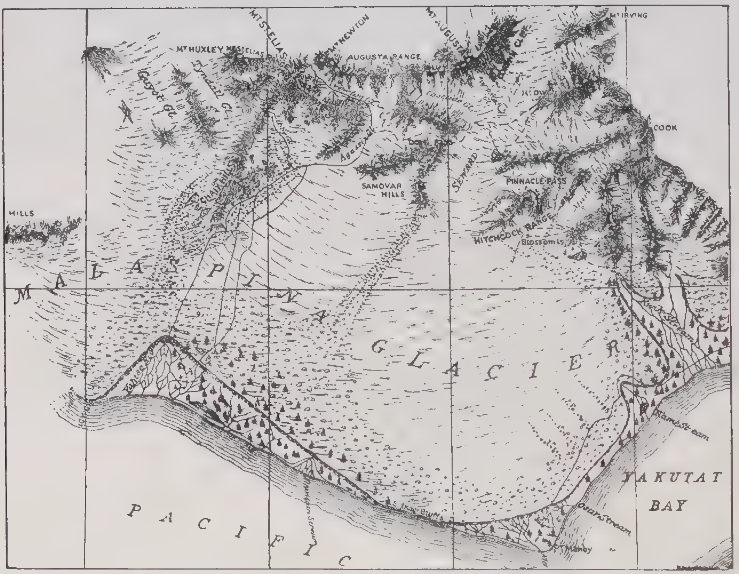


Fig. 7.—Map of the Malaspina glacier, showing the disposition of the moraines, the outwash fan, and the manner in which the forest encroaches on the moraine covered ice. (After Russell.)

The Piedmont Glacier.

When several glaciers unite and the fan of ice upon the plain becomes of considerable dimensions, we have what is known as a Piedmont Glacier. The quaternary glaciers which spread out from the Alps over the plain of Piedmont were of this nature. The best known modern example of this type is the Malaspina Glacier in Alaska, which has been described in detail by Russell. This magnificent sheet of ice exhibits many characters of great interest, not the least remarkable being the profusion of vegetation which grows round about it. A great part of the outwash fan between the glacier and the sea is covered with forest, and trees even grow upon the debris which locally covers the surface of the glacier. The motion of the ice, as is the case in the fans of most Piedmont glaciers, is relatively sluggish, but the phenomena of melting and outwash are of an imposing character. Speaking of the streams which flow from the ice front to the sea, Russell says:

> These rivers issue from the glacier either in a single body of water or in several branches, some gushing out at the base of the bastion formed by the moraine, others from the ice-wall itself at different heights, dashing down from ice caves in grand cascades. Occasionally, after running through a long series of underground passages from the upper valleys to the coast, these torrents are forced to the surface at such high pressure that they shoot upwards like colossal fountains with huge columns of spray. Whatever their origin, they generally divide into numerous branches between the moraine and the sea, and after intersecting the forest in every direction, unite in one or more great streams before reaching the sea.[1]

A most interesting observation of Russell's is that concerning the behaviour of the surface debris. In some places this forms ridges covering the ice. Beneath these ridges the ice is protected from ablation while at the sides it is melted away. The debris comes in time to form a capping to a ridge of ice, and as melting proceeds begins to slide off into the hollows at the side, until in time it forms new ridges in these hollows which in their turn protect the ice beneath, and so on.

> "Thus," says Russell, "the entire surface of the moraine is continually shifting and changing, moving and turning over the masses of stone, breaking them into ever smaller fragments, and finally crushing them into fine sand and mud. During the hot hours of the day, when the ice melts most rapidly, you hear the continual crash of falling stones and the whizzing sound of

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[1] I. C. Russell, "Second Expedition to Mount Saint Elias," *13th Ann. Rep. U.S. Geol. Surv.*, pt. 2. p. 1 (1893).

detritus sliding on icy slopes, mingled with the murmur of torrents, the dash of cascades, and the muffled reports caused by the cracking of the ice."

Glacial sculpture.

A mountain range fashioned by subaerial erosion out of fairly homogeneous rocks, is in general characterised by smoothly-domed uplands intersected by evenly-graded accordant valleys of V-shaped cross section. If such a range is subjected for a more or less prolonged period to the action of mountain glaciers all this is profoundly changed. The main valleys are deepened, widened, and transformed into U-shaped troughs. The lateral valleys lose their accordance and hang on the sides of the main valleys. The valley heads where the

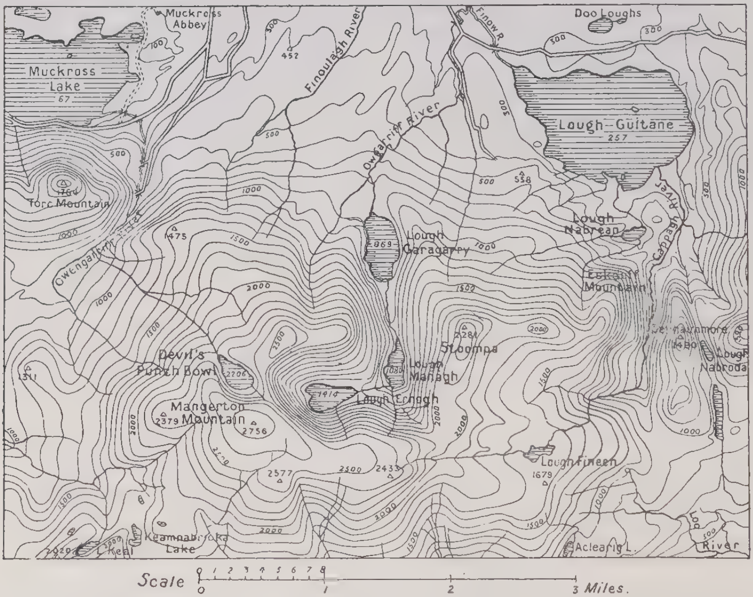

FIG. 8.—Contour map of Mangerton Range, near Killarney, shewing the effects of the action of corrie-glaciers on the northern slopes of a gently-domed mountain mass. The large corrie, containing the three Lakes with "paternoster" arrangement, is the Horse's Glen. Loughs Erhogh and Managh are contained in rock-basins, but Lough Garagarry is held in by a huge crescentic moraine, surrounding the mouth of the glen. Contours every 100 feet. (Based upon the Ordnance Survey Map, with the sanction of the Controller of H.M. Stationery Office.)

glaciers are nourished are expanded into corries which eat their way by head-wall erosion into the heart of the mountain. According to the extent to which this corrie-cutting has progressed the rounded upland may be seen in all stages of dissection. The greater portion of the

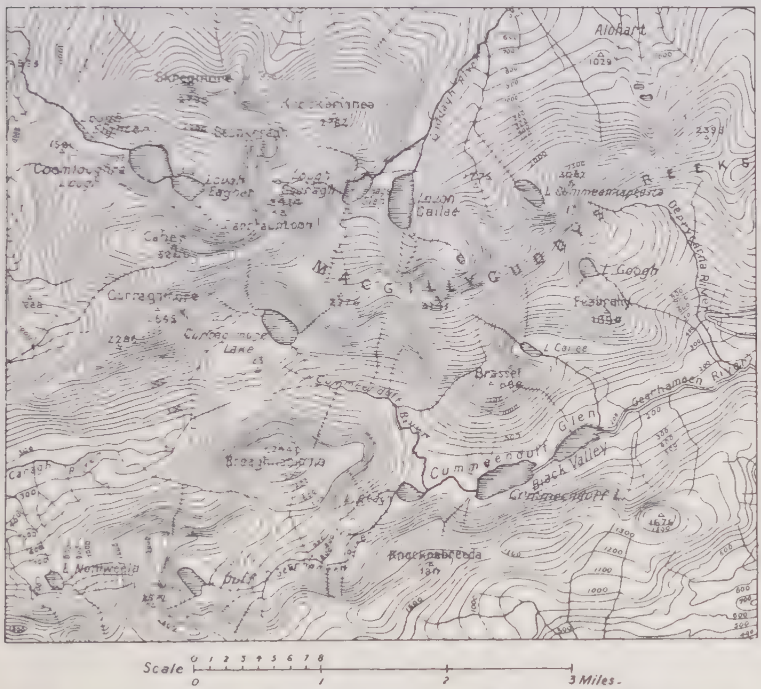

FIG. 9.—Contour Map of Carrantuohill and MacGillicuddy's Reeks, showing the effects of corrie-formation on an originally steep mountain range. Numerous corries have been excavated on all sides of this range, and the slopes of the mountains have thus become considerably steeper. Contours every 100 feet. (Based upon the Ordnance Survey Map, with the sanction of the Controller of H.M. Stationery Office.)

preglacial hill surface may be left, the corries simply showing as isolated gorges here and there. Under more intense conditions the corries may approach one another from opposite sides of the mountain, and finally intersect, leaving narrow arêtes and pyramidal peaks. In the appended contour maps of the Mangerton Range and

Macgillicuddy's Reeks in Kerry, two different stages of erosion are well exemplified.

Pater-noster lakes.

Most valleys which have been traversed by glaciers exhibit a marked unevenness of the valley floor. In addition to the terminal basin caused by the falling off of the erosive action towards the glacier front, numerous smaller rock basins with lakes generally occur all the way up the valley. These are for the most part due to differential erosion in harder and softer rocks. Where a specially hard rib of rock crosses there is almost always a lake on the upper side. From the manner in which they sometimes occur at nearly regular intervals along the draining river they have been referred to as paternoster lakes. Steep steps also occur along the valley, and these may be due either to the varying hardness of the rocks or to the increased erosion produced by the entrance of a tributary glacier.

The continental ice-sheet.

There exist in the world at the present day only two ice-sheets of continental dimensions, that of the Antarctic Continent and that of Greenland. In addition to these there are, however, a number of smaller ice-caps, which resemble the larger sheets in not being dominated by mountain slopes except on their attenuated margins. They generally occupy high plateaus, at the margins of which they discharge by narrow outlet glaciers descending through passes to the lower levels. Fine examples occur in Norway, Iceland, Franz Josef Land, Nova Zembla, Spitzbergen, as well as on some other Arctic Islands. The Balleny Islands in the Antarctic also have similar ice-caps.

Greenland.

The whole of Greenland, with the exception of a bordering rim of mountains, is buried beneath an immense sheet of ice which discharges its surplus accumulation by numerous broad glaciers into the heads of the fjords. The mountainous border varies greatly in width, being widest on the west, and narrowest on the east coast facing the Atlantic. Within the mountains there is a zone of more or less fissured ice out of which rise occasional isolated hills or nunataks. The fissuring of the surface is much greater at the heads of the outlet glaciers. Here also there are large depressions in the

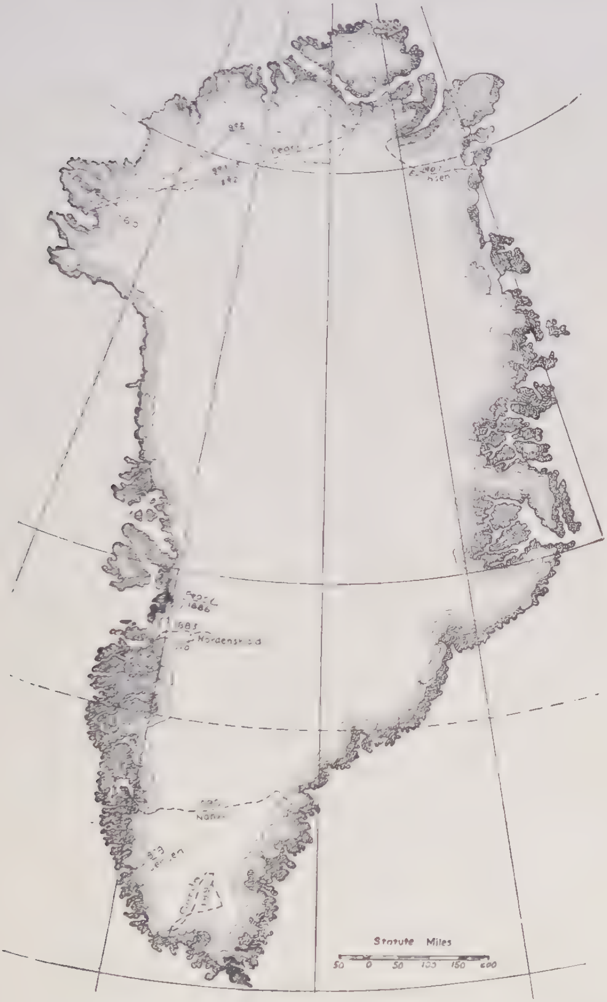

FIG. 10.—Sketch map of Greenland, showing the extent of the inland ice and the routes followed by explorers. (After Hobbs.)

surface of the ice which extend a great distance inland. Peary, when far out of sight of land, was able to locate the position of the outlets by the slope of the surface on the inner margin of the basins. The marginal zone of the ice-sheet is also much melted in summer, so that pools of water lie about on its surface, and streams traverse the ice in every direction. It will not be amiss to quote here Peary's graphic description:

Marginal surface-melting.

> In passing from the margin of the "ice-blink"[1] to the remote interior, from one to five different zones may be noted, the number and width varying with the season, the latitude, and the elevation. In winter the entire surface is undoubtedly covered with a deep, unbroken layer of fine dry snow. Late in the spring the warmth of the sun at mid-day softens the surface of the snow along the low borders of the ice, and this freezes at night, forming a light crust. Gradually this crust extends up into the interior, and with the advance of the season the snow along the borders of the "ice-blink" becomes saturated with water. A little later this zone of slush follows the zone of crust into the interior, the snow along the borders of the "ice-blink" melts entirely, forming pools in the depressions, and streams which cut deep gullies in the ice; water cavities form, old crevasses open, and new ones appear. This zone rapidly widens and extends into the interior in the footsteps of the others, and behind it the immediate border of the ice gets ragged and soiled, pebbles, boulders, and moraines crop out of its melting surface, and by the end of the Arctic summer it is eaten and shattered by the heat, and eroded by the streams, into impassable roughness.[2]

Surface in the interior.

These conditions, however, only obtain in the marginal zone. The interior is a monotonous desert of fine powdery snow. Even where Nansen crossed the ice-sheet, along the 64th parallel, surface melting only takes place during a few of the warmest days in summer, and the moist snow thus produced is at once refrozen into a thin crust. By driving down a rod Nansen proved several such crusts one above the other, separated by a couple of feet of dry powdery snow, which was more compact in the lower layers. All loss by surface melting is practically confined to the marginal zone, and takes place there only during the summer months.

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[1] Ice-blink = ice-sheet.

[2] Peary, *Northward over the Great Ice*, p. lxxii. (London, 1898).

The surface of the inland ice of Greenland has the form of a flat dome, but the altitude which it attains in the unexplored interior is as yet quite unknown. Nansen reached a height of 9000 feet in crossing on the 64th parallel, and a height of close on 8000 feet was attained by Peary in his traverse across the north end of Greenland. The highest point on the 64th parallel lies to the east of the median line of the country, and Peary is of opinion that the same holds of the north end.

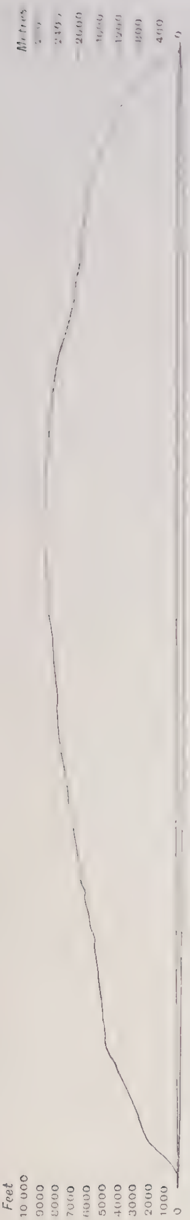


FIG. 11.—Cross section of Greenland, showing the form of the upper surface of the inland ice along the route followed by Nansen. Vertical scale × 10. The lower line exhibits the same cross section drawn to a true scale. (After Nansen.)

Nature of the snow-fall.

All the explorers who have penetrated into the interior are agreed as to the fine-grained character of the snow which falls there. Among the most interesting of the observations made by Nansen are those bearing on the origin of this snow. He calls attention to the great clearness of the atmosphere during nearly the whole of the time occupied by his journey. On only a few days was the sky overcast, and when snow was falling it was still possible to see the sun. The fine dusty snow appears to be precipitated directly from the lower layers of the atmosphere without the preliminary formation of clouds. It is what is known as frost snow in some parts of Norway.

Temperature.

The clearness of the atmosphere over the ice-sheet and its poverty in carbon dioxide, facilitate radiation, and proportionately increase the daily and also, no doubt, the seasonal range of temperature. During Nansen's journey the temperature at the highest levels seldom rose much above 0° F., and at night it generally sank to $-40°$ F., and in one case to $-50°$ F. In the north of Greenland Peary registered a temperature of $-66°$ F. We invite particular attention to these temperature records, since there has been a tendency of recent years to regard precipitation as a more important factor than cold in producing glaciation. Peary says:

> There is no doubt in my mind that in the middle of the Arctic night, in the centre of this "Great Ice," lifted a mile and a half or two miles into the frozen air that sweeps around the pole, separated from any possible effect from the earth's radiated heat by a blanket of ice and snow a mile or more in thickness, and distant fully two hundred and fifty miles from the possible ameliorating effect of the Arctic seas, there is to be found the fiercest degree of cold of any spot upon the surface of the globe.

Radial winds.

Another most important result of the exploration of Greenland is the discovery of the radial character of the prevalent winds, from which it may be inferred that there exists a more or less permanent anticyclone over the ice-sheet. Nansen first announced this discovery in the year 1890, stating that the winds which prevail on the coasts have an especial tendency to blow outwards at all points. Peary's observations have amply confirmed this conclusion. Speaking of his experience of the western and northern coasts he says:

> The regularity of the winds of the "Great Ice" of Greenland, as I have found them during an actual sojourn of over seven months upon the "Great Ice," and visits to it of greater or less duration in every month of the year, is phenomenal. Except during atmospheric disturbances of unusual magnitude, which cause storms to sweep across the country regardless of ordinary rules, the direction of the wind of the "Great Ice" of Greenland is invariably radial from the centre outwards, perpendicular to the nearest part of the coast-land ribbon. So steady is this wind, and so closely does it adhere to this perpendicularity, that I can liken it only to the flow of a sheet of water descending the slopes of the "Great Ice" from the central interior dome to the

coast. The direction of the nearest land is always easily determinable in this way: the neighbourhood of great fjords is always indicated by a change in the wind's direction; and the crossing of a divide, by an area of calm or variable winds, followed by winds in the opposite direction, independent of any indications of the barometer.

Transporting effect of winds.

The effect of these radial winds in preventing unlimited accumulation of ice and snow is also emphasised by Peary. Continuing, he says:

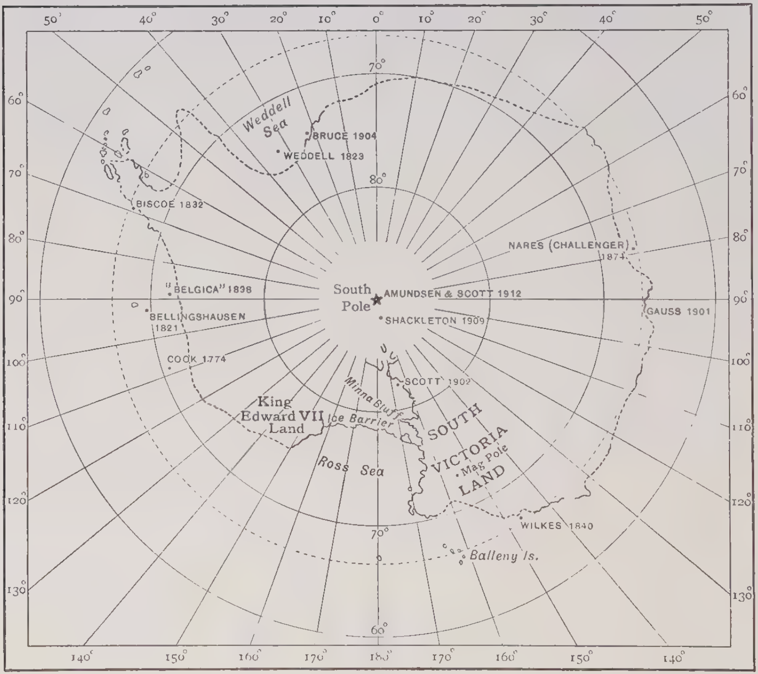
> The opinion was advanced by me immediately on my return in 1892, that the transporting effect of the wind upon the snow of the ice-cap must be counted as one of the most potent factors in preventing the increase in height of the ice-cap; a factor equal perhaps to the combined effects of evaporation, littoral and sub-glacial melting, and glacial discharge. This opinion has been corroborated and greatly strengthened by my later observations. When it is remembered that the flow of the atmosphere from the cold heights of the interior ice-cap to the lower land of the coast is going on throughout the year with greater or less intensity, and that a fine sheet of snow is being thus carried beyond the ice-cap to the ice-free land at every foot of the periphery of the ice-cap, there to melt, it will perhaps be seen that the above assumption is not excessive.

Foehn winds of the margin.

A curious and rather important result of the anticyclonic conditions and the resulting descent of air over the central portions of the ice-sheet and its radial outflow to continually lower levels, is the presence along the coasts of warm, dry foehn winds from the interior of Greenland. These were first noted by Rink on the west of the country in 1877, but have since been observed to occur on other parts of the coast. They are due to the heating of the air by compression as it descends to lower levels.

The Antarctic.

The greater part of the region within the Antarctic Circle is occupied by land. This continent, now called Antarctica, nourishes the greatest ice-sheet in the world. It is not so well known as that of Greenland, for most of the exploring expeditions, as will be seen from the map, have only succeeded in touching on its margin. In that part of its coast, however, which lies due south of New Zealand, a considerably greater measure of success has rewarded the efforts of the expeditions under Scott[1] and Shackleton.[2] Here the coast, which for long distances to the west practically coincides with the Arctic Circle, turns away south and forms a great bay known as the Ross Sea. On the west of this bay are the lofty mountains of South Victoria Land, behind which lies the plateau of the inland ice. On the east is King Edward VII. Land of which little is yet known. The south side of the bay is formed, not of land, but of a vertical wall of compacted snow, discovered by Ross in 1840, and after-



Emery Walker sc.

FIG. 12.—Map of the Antarctic Continent, showing its supposed outline, the points reached by explorers, and the position of the Ross Barrier. (After various authorities.)

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[1] R. F. Scott, *The Voyage of the Discovery* (London).

[2] E. H. Shackleton, *The Heart of the Antarctic* (London, 1909).

The Ross Barrier.

wards known as the great Ross Barrier. It extends a distance of 500 miles from King Edward VII. Land to South Victoria Land, and varies in height from 20 feet to 280 feet. Great tabular bergs continually break away from the cliff and float off to the north. Observations made by Shackleton's expedition of the depth of water in which one of these came to ground showed that only half of its depth was below water, and it must therefore have been composed throughout of compacted snow and not of ice. Scott, moreover, proved by taking soundings close to the face of the Barrier that it is afloat along the entire length. When the *Discovery* was anchored in Balloon Inlet near the eastern end of the Barrier, the snow cliff rose and fell with the ship according to the state of the tide. Indeed the experiences of the expedition at this spot prove beyond a doubt that the tide sets in and out beneath the Barrier with considerable force. When the ship arrived in the inlet little or no pack ice was visible, but very shortly with the turn of the tide it came crowding in on a strong current which ran towards and under the ice at the head of the inlet. Among the pack ice were several small bergs, one of which barely escaped crushing the ship. On the following morning the bergs and pack ice, which gave the explorers an anxious night in this otherwise secure looking harbour, took themselves out to sea again in the same manner as they had entered on a current which now set from beneath the ice out towards the mouth of the inlet. As a sounding here gave 315 fathoms it is possible to form some conception of the volume of water which passes in and out beneath the ice-sheet at every rise and fall of the tide.

From the top of the cliff the surface of the Ross Barrier can be seen stretching away south as a uniform plain of snow without any noticeable change of altitude. It is bounded on the west by a lofty range of mountains, the continuation of the coastal range of South Victoria Land. The expeditions of Scott and Shackleton went south along the western edge of the Barrier, and proved that it remains practically horizontal for a distance of at least 300 miles to the south. From the plateau of inland ice on the far side of the mountains immense glaciers descend through the passes and push out into the Barrier, causing great fissures and pressure ridges for some considerable distance from land. From measurements made by both expeditions in the neighbourhood of Minna Bluff it appears that the Barrier Ice is moving northwards towards Ross Bay at a rate of about $\frac{1}{3}$ of a mile per year. This motion is no doubt due to the thrusting action of the great glaciers which are tributary to the Barrier Ice. It is curious, however, that none of this glacier ice ever reaches the Barrier front. Nothing but compacted snow is to be seen there. The explanation of this has been pointed out by David and Priestly, the geologists to Shackleton's expedition. From observations on the depth to which an old depot of Scott's had become buried during the interval between the two expeditions, it was proved that a little over a foot of compacted snow is added to the Barrier surface every year. Now a portion of the Barrier formed, say, of glacier ice, some 300 miles inland would, at the rate of $\frac{1}{3}$ of a mile per year, take 900 years to reach the Barrier face, and it is clear that it would then be covered by 900 feet of snow. As the snow at the cliff both above and below water is nowhere more than about 600 feet thick, it would appear that not only the original glacier ice, but a considerable quantity of the superincumbent snow has disappeared from its base. David and Priestly suggest that it has probably been thawed away by the tidal waters circulating beneath the Barrier.

Motion of the Barrier Ice.

Ice-sheet of the interior.

The inland ice which lies to the west of the coastal range of South Victoria Land has been penetrated in three places. During his second year in the south Scott ascended the Ferrar Glacier, and reached the unbroken ice-sheet 70 miles from the coast at an altitude of 8900 feet. Here he found himself on a great snow plain with a level horizon all round, broken only to the east by the tops of the mountains through which he had come.

On this plain he pushed due west for about 200 miles, his altitude as given by the barometer not varying more than 60 or 70 feet throughout the journey. The ice, therefore, has no gradient in this direction. The expeditions of David and Shackleton, however, prove that it has a gradient from north to south. David's party ascended on to the plateau opposite the Drygalski Ice Barrier Tongue in latitude 75° S., and travelling north-west for 260 miles reached the magnetic pole, which lies on the plateau at an altitude of 7260 feet. The highest point passed lay to the south-east of the pole, but was only 90 feet higher. The surface of the ice-sheet is almost as level here as it was further south where traversed by Scott, but about 1500 feet lower. Shackleton ascended along the Beardmore Glacier, which being about 50 miles broad forms one of the principal outlets of the inland ice. He reached the unbroken plateau in latitude 86° at about 8000 feet, and ascended steadily to the south, until at latitude 88° 23′, his furthest south, he reached an altitude of 10,050 feet.

Extent and gradient.

There is every reason to believe that the plateaus traversed in these three journeys form parts of a continuous sheet of snow and ice which extends from north to south a distance of at least 1200 miles. How far it extends west from the coastal mountains is hard to say, but it has been proved by Scott and David to be unbroken for 200 miles. In the east and west direction there is as we have remarked above no gradient, but in a north and south direction there is a rise of 3000 feet in 1200 miles, which is equivalent to an average gradient of $2\frac{1}{2}$ feet per mile.

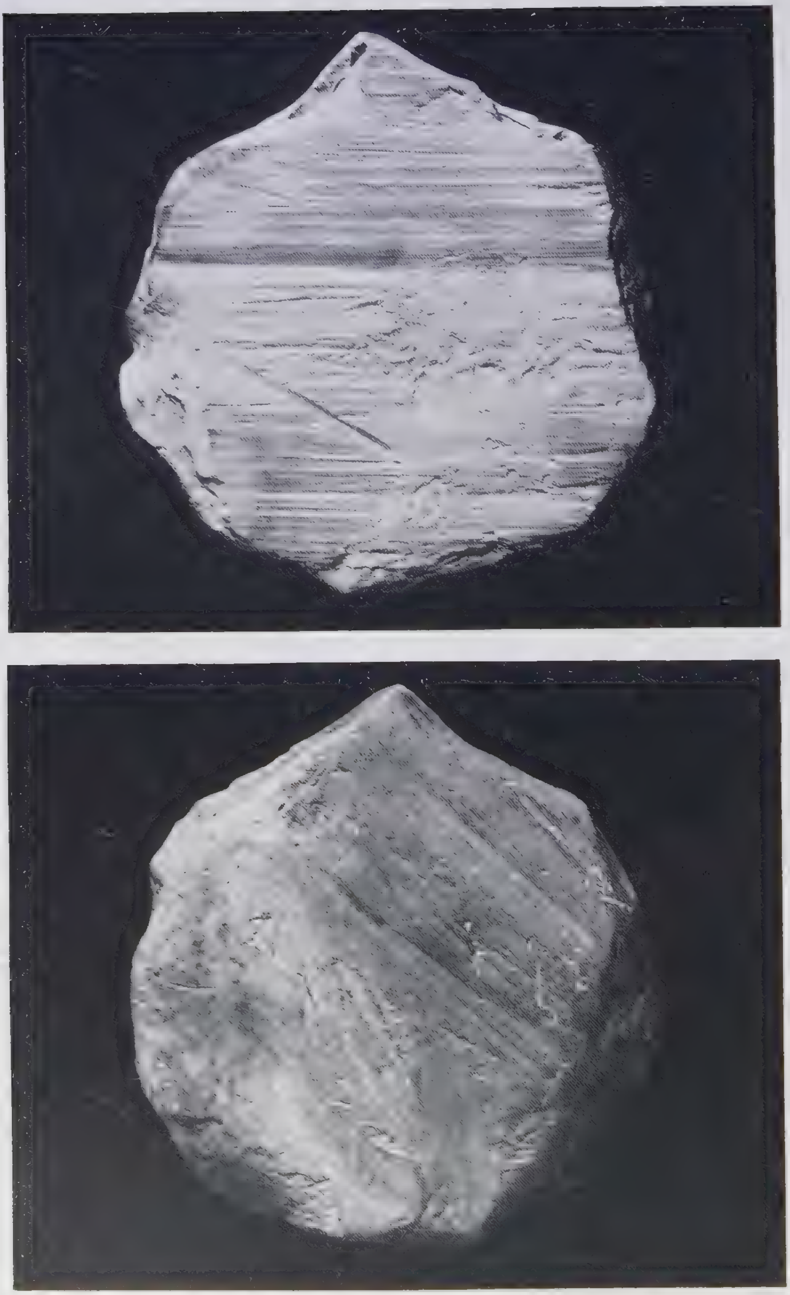
Snowfall and winds.

The conditions on the inland ice of the Antarctic have been found to be very similar to those of Greenland. The greater portion of the snow is fine grained and dry, and is precipitated from an otherwise clear atmosphere. The wind is an important transporting agent, and no doubt plays an effective part in limiting the growth of the ice-sheet. The prevalence of easterly and south-easterly winds at most parts of the coast of Antarctica, which have been approached by vessels, shows the existence of marked anticyclonic conditions over the continent. One of the greatest hardships of Shackleton's journey was the persistent strong winds from the south, amounting on certain days to blizzards which stopped progress entirely. The existence of an area of high pressure over the South Pole, as was indeed pointed out by Sir John Murray as early as 1893, may now be regarded as entirely proved. In view of the *a priori* probability of the conclusion, it would not be going too far to generalise from the two cases before us, and infer that any ice-sheet of sufficient size must necessarily to a large extent determine its own climatic and meteorological conditions. The importance of this in connexion with the quaternary ice-sheets has been fully recognised by Harmer (see p. 100).

The glacial anti-cyclone.

We are, I imagine, hardly yet in a position to say definitely whether the power possessed by a large ice-sheet of establishing an anticyclone over its surface has a stimulating or restraining effect on its growth. One point is quite clear, and that is that there is an essential difference in the mode of nourishment of the great ice-sheets and the smaller ice-caps and mountain glaciers. The latter depend on precipitation determined by external causes, such as the latitude and the distribution of land and water in adjacent regions. A great ice-sheet once established sets up a machinery of its own, which is constant in its action and practically independent of external causes.

PLATE IV.



TWO VIEWS OF A GLACIATED BOULDER SHOWING THE STRIAE RUNNING IN DIFFERENT DIRECTIONS ON OPPOSITE SIDES.

From photographs by Godfrey Bingley.

To face p. 27.

CHAPTER II

THE GLACIAL DRIFTS

The various types of end-moraine—Englacial moraine—Ground-moraine or boulder-clay—Gravels associated with the boulder-clay—Nature of the deposits dependent on the size of the glacier—The glacial series of the Alpine glaciers—Different effects of advancing, retreating, and stationary glaciers—Conditions essential to the production and preservation of the glacial series—The end-moraines of continental glaciers—Drumlins—Theory of drumlins—Boulder-clay plains—Outwash gravels, kames, and eskers—Theory of eskers—Gravels interstratified with the boulder-clay—Marginal gravels—Striation and ice-moulding—Roches moutonnées.

In the preceding chapter a distinction has been drawn between different types of glaciers in terms of the extent of their development. This classification has a marked advantage in that it is possible to trace corresponding modifications in the deposits. As such modifications depend largely on the proportions of material borne on the surface of the ice to that carried forward in its mass or dragged along beneath its sole, it is important to consider to what extent these modes of transport are distinct and result in distinct types of deposit.

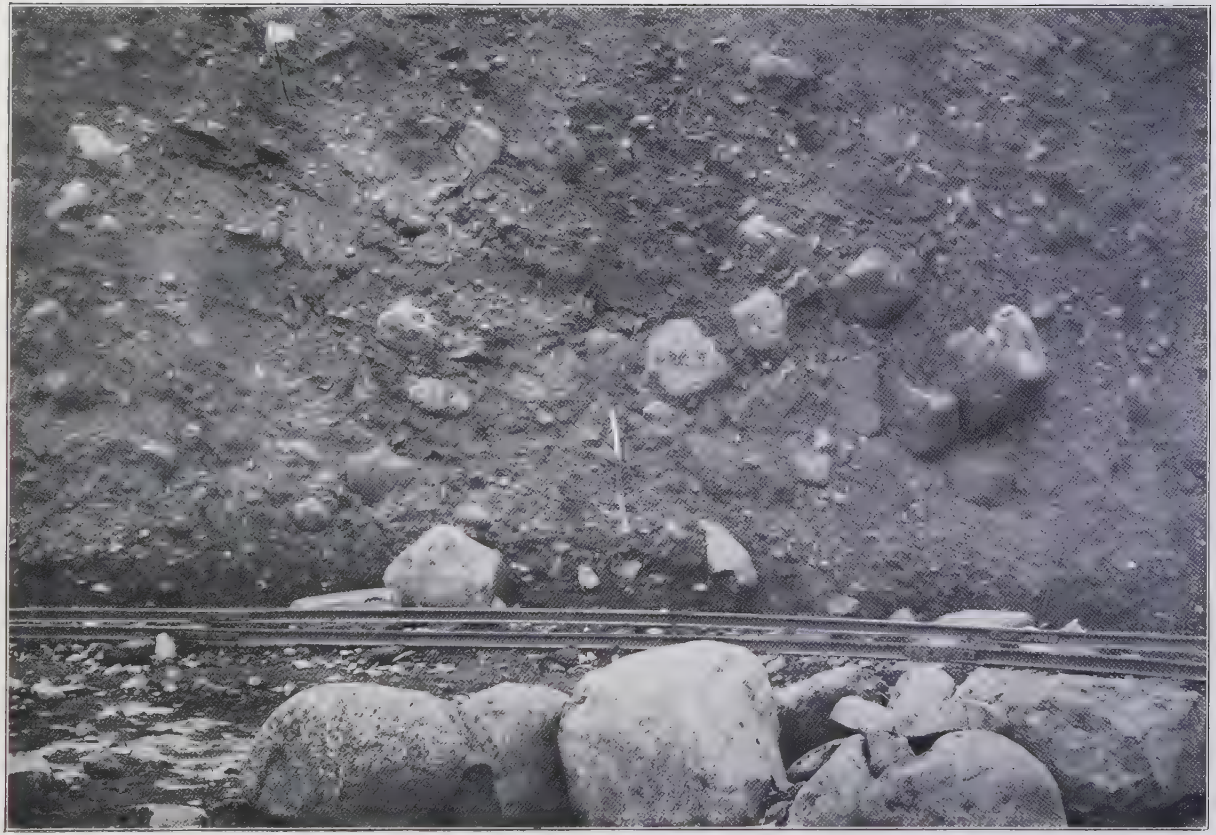
The mode of formation of the various types of end-moraine.

The material borne on the surface of the ice consists for the most part of angular debris fallen on to the glacier from dominating slopes or cliffs. It remains to a large extent on the upper surface, and generally suffers little abrasion, being finally shovelled off at the end of the glacier to form the type of end-moraine known as *rubble-moraine*. Large blocks are also carried along in this way, and are to be found stranded in all sorts of positions in areas formerly covered by glaciers. They sometimes form a large proportion of the end-moraine, which is then known as *block-moraine.* A certain amount of material originally embedded in the ice comes also to be exposed on its surface by the general process of ablation, and as this may be more or less rounded or striated, a certain small proportion of ice-moulded stones may be found in the rubble-moraine of most glaciers. In the case of small glaciers dominated by steep slopes the proportion must, however, be very small, while large glaciers and ice-sheets have generally very little surface moraine. The larger blocks resting on the surface protect the ice beneath from ablation and often become raised on pillars of ice, forming the well-known glacier tables. On the other hand, smaller stones and dirt are liable to sink into the surface by absorbing the sun's rays and melting the snow and ice beneath them. The peculiar shuffling action described in the last chapter as going on on the surface of the Malaspina Glacier must lead to a certain amount of rounding of the surface material.

The debris carried in the body of the ice is generally known as *englacial material.* It may be derived either from the surface of the glacier, by the falling of material into crevasses and pot-holes, or from its sole by a process of overriding, whereby the lower layers of the ice are carried forward over those in front. It is observed in many glaciers that the dirt layers are not parallel to the floor, but make an angle with it, rising in level towards the front of the glacier. A considerable amount of rounded and striated material thus becomes incorporated in the ice, and is finally extruded by terminal melting as another type of end-moraine known as *boulder-moraine,* and characterised by the presence of abundant ice-moulded stones.

The englacial material of ice-sheets may give rise to

In the case of large ice-sheets which, deprived of their sources of supply, become dead ice and decay in place, the englacial material settles down as a layer on the surface of any deposits formed beneath the ice



SECTION OF BOULDER-CLAY IN BARTON QUARRY, N.E. OF RICHMOND, YORKSHIRE.

Boulders of Shap Granite and of the Whin Sill in the foreground.

From a photograph by Godfrey Bingley.

To face p. 29.

when it was in motion. The upper boulder-clay of many districts, generally not more than 5 feet in thickness, and characterised by its loose loamy nature and the high state of oxidation of its materials, is very probably formed in this way.

upper boulder clay.

By far the most considerable portion of the debris transported by large glaciers is dragged along beneath or in the bottom layers of the ice, and is known as the *subglacial-* or *ground-moraine*. There is generally no clear distinction between it and the englacial moraine, for the lower layers are often heavily charged with boulders and dirt, and pass gradually into the frozen mud beneath. The materials are derived to a large extent from the abrasion of the rocks over which the glacier or ice-sheet passes, the rock fragments thus incorporated in the sole of the glacier being employed as tools for the carrying on of the work. Owing to the high pressure under which it is formed, and the fineness of the rock-flour which forms the matrix, the ground-moraine becomes much compacted, and, when finally abandoned by the ice, forms the stiff, tenacious deposit known as *boulder-clay*.

The ground-moraine gives rise to the boulder-clay proper or till.

Boulder-clay is the commonest of the drift deposits in all glaciated regions. In its typical form it is a stiff, tenacious, unstratified clay full of subangular stones of various sizes, and lying in all positions in the clay. These stones and the matrix in which they are embedded are for the most part derived from the immediately underlying rock, but contain nearly always a considerable admixture of material of distant origin. Whether local or foreign, however, the stones are mostly covered with scratches or *striae*, which sometimes cross one another in all directions, but more commonly follow a predominant direction or even show a strict parallelism. The tenacity of the clay matrix is so remarkable that the boulder-clay has long been known to engineers as one of the most difficult of all deposits to cut through. It is very expensive to blast, even heavy charges producing only a slight effect, and has to be removed almost

Character of the boulder-clay.

entirely with pick and spade, the use of which is greatly hindered by the numerous firmly embedded stones.

Gravels associated with the boulder-clay.

The circulation of subglacial waters beneath the lower reaches of glaciers and the margins of ice-sheets produces considerable quantities of gravel, sand, and laminated clay. These are to a large extent deposited outside the edge of the ice, but also frequently come to rest beneath it. In the latter case they are found, on the melting of the ice, to lie between the ground-moraine and the englacial moraine, and the commonly observed phenomenon of an upper and lower boulder-clay separated by gravels is thus produced. On the other hand, subglacial gravels, sands, and silts may be destroyed by subsequent motion of the ice, and reincorporated in whole or in part in the ground-moraine. In this way are produced most of the irregular wisps of sand and gravel found in the boulder-clay, and cases of a gradual passage from one to the other have a similar explanation. The effects of less pronounced motion are visible in the contortions of bedding frequently exhibited in glacial sands and gravels.

Types of moraine.

Let us turn now to the various classes of glacier and consider first the smallest. The mere snow-slope effects no erosion of its floor, and its "moraine" consists entirely of scree which has fallen upon its surface and slid down to its outer margin. Whether there is actually any transport of material owing to motion of the snow and ice depends entirely on the size and thickness of the snow-slope, which ultimately passes into a corrie glacier. In the case of the latter, in addition to the sliding action on the surface, there is also a certain amount of transport through ice motion and considerable erosion of the floor. Passing to the valley glacier we find the surface transport still playing an important part, so that the end-moraine may be entirely or to a large extent a rubble-moraine or block-moraine. It may, however, be composed largely of englacial material, and is then a boulder-moraine. Another type of boulder-moraine may arise through the thrusting forward and ridging up in front of the ice of masses of ground-moraine or gravel. This is the *Staumoräne* of the Germans, a term for which I know no phonetically pleasing English equivalent.

Deposits of the Alpine glaciers

Boulder-clay is not a typical product of valley glaciers, although it may be produced by them, especially when they deploy upon a plain and thus take on the character of a Piedmont ice-sheet. The great glaciers which poured forth from the Alpine valleys during the Ice Age were of the Piedmont type, and have left behind them a regular series of deposits, which recur with remarkable regularity all round the Alps. Prominent everywhere is the semicircular *end-moraine*, consisting either of a single ridge or a series of more or less parallel ridges. Outside this stretch the *outwash gravels*, inside it is the *ground-moraine* district. The latter is generally basin-shaped, the *central depression* being frequently occupied by a lake or alluvial flat. Occasionally the basin is open, having an outlet sufficiently low to prevent the accumulation of water in its bottom. In the centre of the basin the covering of ground-moraine is thin and irregular, and ice-moulded knobs of rock (*roches moutonnées* or *Rundhockorn*) project through it. Outside this, as the ground slopes upwards towards the moraine, the drift is thicker and forms numerous elongated ridges or *drumlins* with their axes parallel to the direction of ice motion. In the centre of the bow of the end-moraine the drumlins are perpendicular to the moraine, but towards the sides they make an angle with it. The relations are shown diagrammatically in Fig. 13.

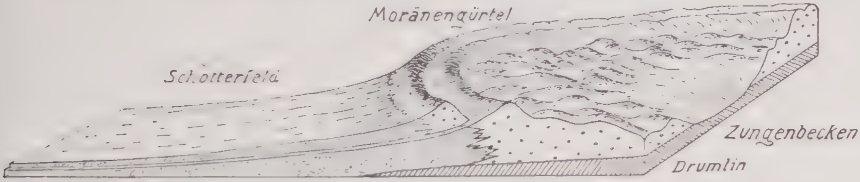


FIG. 13.—The typical glacial series of the Alpine glaciers. The members are, from within outwards: (1) The central basin (Zungenbecken), (2) The drumlin-belt (Drumlin), (3) The moraine-belt (Moränengürtel), (4) Outwash fan (Schotterfeld.) (After Penck.)

The glacial series.

The four members here described—central basin, drumlin zone, moraine belt, and gravel sheet, are termed by Penck the "glacial series," and are found wherever any large valley or Piedmont glacier has maintained a constant development for a considerable length of time, or has only exhibited minor oscillations. An advancing glacier forms outwash gravels, moraine belt, and drumlin zone, but continually advances over and destroys or redistributes them. A retreating glacier also, as long as it is not merely dead ice, deposits end-moraines and gravels, but distributes them thinly and irregularly over the valley floor, thus masking the subglacial topography as it retreats. For the perfect development and preservation of the typical glacial topographic series a long continued maximum and a rapid retreat therefrom seem to be demanded.

Active precipitation and decay are essential to the production of end-moraines.

It is desirable here to call attention to the essential condition for the production of end-moraine by a glacier or ice-sheet. This condition is that there should be active motion of the glacier ice up to the decaying margin, so that sufficient material is carried forward to this line and deposited there. Dead ice can never make an end-moraine no matter how long it persists. On the other hand copious precipitation and active decay are extremely favourable to the production of end-moraine, and when these are nicely balanced, as seems to have happened at certain stages during the Ice Age, immense terminal ridges may be produced.

The end-moraines of continental ice-sheets.

In the case of continental ice-sheets, the surfaces of which are only dominated by a few isolated hills or nunataks, the effect of surface transport is negligible. End-moraines of the rubble-moraine type are therefore entirely wanting, their place being taken by boulder-moraines, produced either by the terminal extrusion of englacial material, or by thrusting, as in the case of the "stau-moräne" mentioned above. The Quaternary Ice-Sheets during their greatest development appear to have produced very little end-moraine, but at a later stage, when of diminished size, they formed immense belts, of which the Baltic end-moraine belt and the great kettle-moraine of America are the most famous. A characteristic of these belts is the presence of isolated basins, known as giant's kettles, containing a pond or marsh and without surface outlet. These are generally supposed to have been formed by the inclusion in the moraine of masses of ice, the subsequent melting of which has left a hollow. This is doubtless in many instances the correct explanation, but it is clear also that the irregular dumping of ridges and mounds of debris will in itself inevitably produce many enclosed basins.

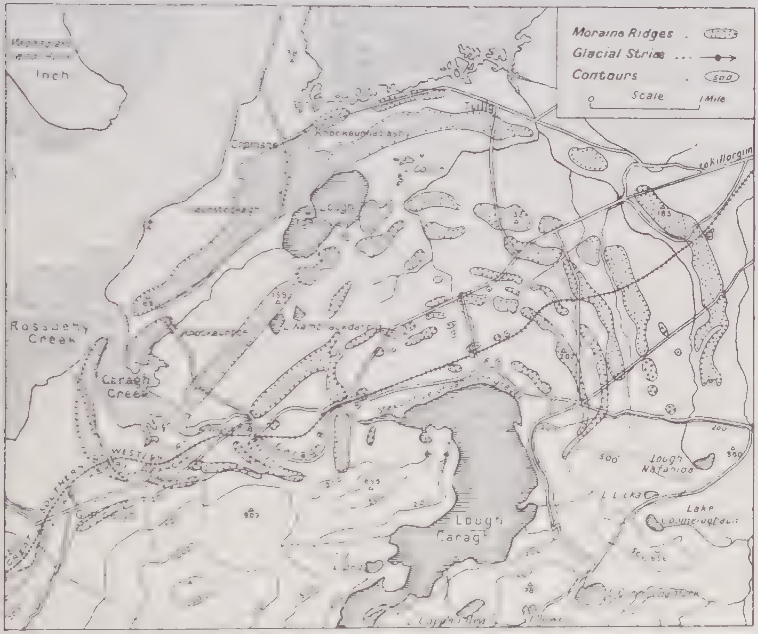


FIG. 14.—Crescentic moraines round the mouth of the Caragh Valley in Co. Kerry. Lough Caragh occupies the central basin from which the glacier deployed. A noteworthy difference from the Alpine glacial series figured above is the absence of a drumlin belt. (Based upon the Ordnance Survey Map with the sanction of the Controller of H.M. Stationery Office.)

Moraine mounds are among the most intelligible of all topographic features resulting from ice-invasion. We can study their formation round the edges of the ice-sheets of the present day, and so get a clearer insight into their meaning than would be otherwise possible. We have thus learned to classify them into terminal and frontal, marginal and interlobate, and to attach a certain significance to these and other distinctions, which is of service in the interpretation of those formed in Quaternary times. With regard, however, to the great mass of the drifts evolved beneath the ice, and impressed while in that position with their characteristic forms, we have no such opportunities for comparison. The origin of such ground-moraine features as drumlins and the infinite variety of forms assumed by subglacial gravels we can only infer on theoretical grounds from a consideration of the characters which they exhibit, and of the physical properties and behaviour of ice moving under great pressure.

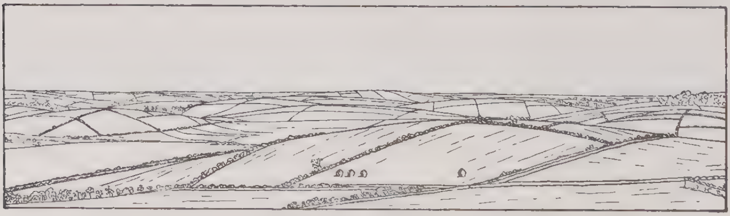


FIG. 15.—Subdued drumlin-topography in the neighbourhood of Pettigo, Co. Donegal. The drumlins are viewed side on.

Drumlins.

In discussing the glacial series of the Alps reference has been made to the drumlin belt lying between the central depression and the end-moraine. Here the ground-moraine is moulded into ridges parallel to the direction of ice motion. The boulder-clay of the continental ice-sheets of Quaternary times assumes in many districts a similar surface form. As in the Alpine Valleys the drumlins are lenticular mounds of boulder-clay of oval outline with their long axes parallel to the direction of ice-flow. Their form has been graphically described as hog-backed or whale-backed, and varies from circular to extremely long and elliptical. Very commonly they are from 50 to 100 feet in height, several hundred yards long and about half that width. They vary much in size, however, and in places attain a length of half a mile or even a mile, and are several hundred feet high. Those in the Scottish lowlands east of Glasgow attain immense dimensions. The grouping together of innumerable smaller drumlins produces the peculiar "basket of eggs" topography, so well seen in certain districts such as north County Down in Ireland. In America, according to Russell, they sometimes take the form of half a cigar cut lengthways, the blunter end being towards the point of the compass from which the depositing ice came. The origin of these peculiar hills

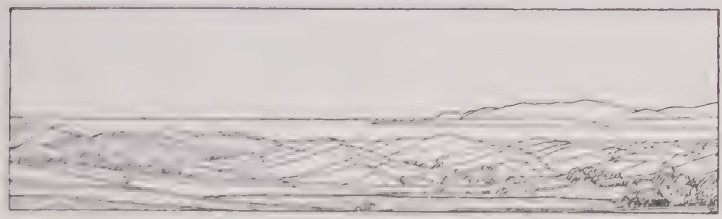


Fig. 16.—Pronounced drumlin topography in the neighbourhood of Ballintra, Co. Donegal. The drumlins are viewed from the upstream end. Donegal Bay and St. John's Point in the distance.

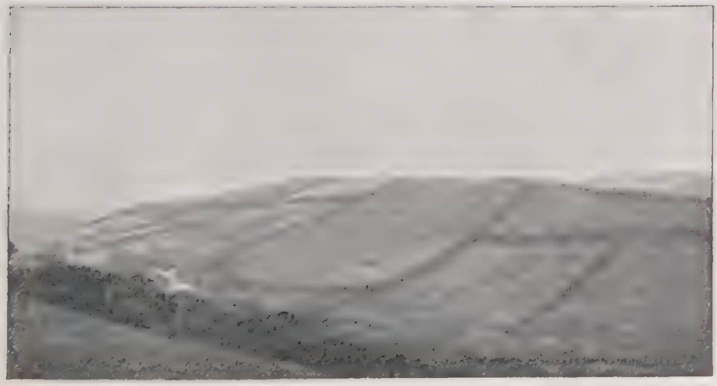


Fig. 17.—Drumlin in the neighbourhood of Ballintra, Co. Donegal, viewed obliquely from the upstream end.

Theory of the origin of drumlins.

is still a mystery. They have, of course, never been observed in process of formation, and are not even known in association with any existing ice-sheet, so that we get little help from this direction except the indication that they are deep-seated products of the ice. Of the many theories that have been advanced concerning them, perhaps the most plausible is that recently put forward by Russell in his *Glaciers of North America.* He regards the drumlins as formed beneath the ice-sheet in its more central portions. Any portion of the ice which is heavily charged with debris is, as a consequence of the presence of this debris, less "plastic" and resists the differential motion by which the glacier moves onward. If it happens to be in contact with the bottom it comes to rest, while the clearer ice around flows by and over it, moulding it into a less resistent lenticular shape, and adding to it any foreign matter which the ice motion happens to bring in contact with it. There results a lenticular hill of boulder-clay which from its shape offers little resistance to the ice motion, and may thus persist until the decay of the glacier, provided there is no great

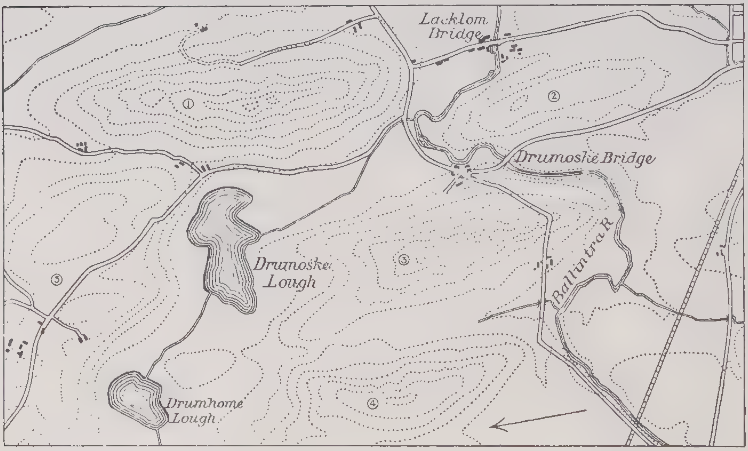


Fig. 18.—Contour map of drumlin-topography, in the neighbourhood of Ballintra, Co. Donegal. The arrow shows the direction of ice-motion.

change in the direction of ice motion. The essential condition, then, according to this theory is an unequal and irregular distribution of the debris carried by the glacier. If the ice is lightly and uniformly charged with dirt, it will no doubt bear it all forward ; if it is heavily, but still uniformly charged, it will probably deposit it in a smooth sheet of till ; if it is unequally charged, concentration of the dirt will take place about the less plastic heavily charged masses. Although Russell himself does not suggest it, yet we may consider that the excessive friction produced by the resistance to motion in the neighbourhood of these nuclei, might develop sufficient heat to cause local melting,[1] and so facilitate the segregation of the material. The hypothesis as a whole gains support from the fact that drumlins are often found to have been accumulated round a projecting knob of rock as a nucleus, while their laminated structure, remarkable compactness, and general flowing outlines are also in harmony with this view of their origin.

Boulder-clay plains.

The drumlin type of topography which is characteristic of the ground-moraine district of the ancient Alpine glaciers is, however, the exception rather than the rule in the drift sheets of the Quaternary glaciation. The boulder-clay of these drift sheets is commonly spread out in level or gently undulating plains possessing little variety of surface feature. The prevailing effect of glaciation is to level down inequalities, removing prominent ridges and filling up hollows. There is thus produced in many regions a monotonous uniformity of landscape, which the denudation of post-glacial times has but little availed to modify.

Outwash gravels, kames and eskers.

The circulation of sub-glacial waters within or beneath the margins of glaciers and ice-sheets produces by the washing of the englacial moraine and ground-moraine quantities of gravel, sand, and silt, which may be carried beyond the limits of the ice or deposited beneath it. In the first case an outwash fan is generally produced, but, if the glacier stream happens to open into standing water, such as the sea or a lake, a typical delta may also be built. By far the larger part of the sand and gravel produced by the melting of the ice and the circulation of the resulting water is thus disposed of. A smaller quantity, however, comes to rest in the sub-glacial channel itself, and on the melting away of the ice may be left as mounds and ridges of gravel. In this way it is supposed that the isolated mounds known as *kames* and the elongated ridges called *eskers*[1] (Swedish *åsar*, American *osars*) are produced.

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[1] The melting point at the sole of a glacier is much lower than at the surface on account of the much greater pressure. It is probable that the ice at the sole tends to be always at melting point.

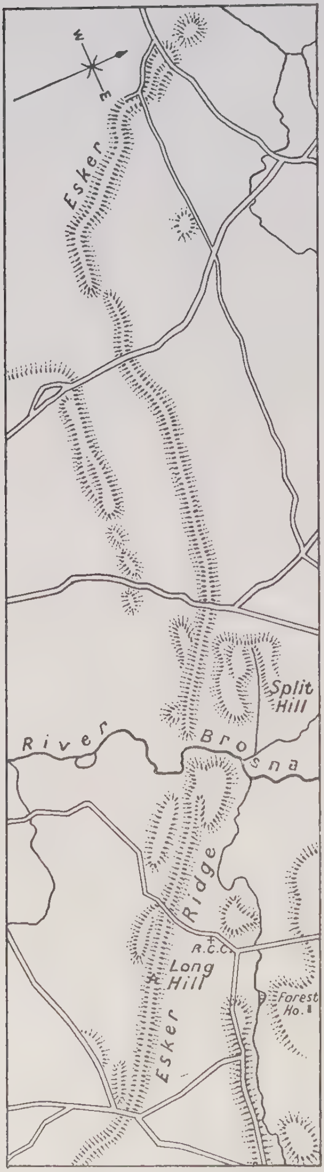

Fig. 19.—Sketch map of portion of an esker near Tyrrell's Pass, in the central plain of Ireland.

Eskers are winding ridges or strings of mounds composed of water-worn sand and gravel. They exhibit in section distinct cross or current bedding, as well as contortion, faulting and other disturbance, which can only be ascribed to the presence of ice during their formation. They frequently show in their course across country a distinct disregard for the present surface gradient, thus proving that the streams which deposited them could not have flowed entirely on that surface, or else must have been under sufficient hydrostatic pressure to flow uphill. On the whole there is little doubt that these curious ridges mark the courses of sub-glacial or englacial streams, but the precise mode of their formation is still a matter of speculation. The prevalent idea regarding them is that they are the casts of these streams, the channels of which are supposed to have become partially or entirely choked with debris. It is obvious, however, that the bedding of any deposits formed thus in sub-glacial channels at a little distance from the edge of the ice-sheet would soon be destroyed by the motion of the ice, and, although we find abundant signs of disturbance in eskers, yet the greater part of the bedding is frequently quite undisturbed. We may therefore fairly conclude that they are more or less marginal deposits; perhaps entirely marginal. At the extreme edges of recent ice-sheets the channels of sub-glacial streams often enlarge into great glacier vaults, or even become open to the sky, and it is possible that in such open portions the esker gravels may have been laid down, the small patches of boulder-clay said to have been found in some cases on

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[1] The Swedish word *ås* used by some authors to denote these chains of gravel mounds does not seem suited for use in English, while to employ its plural *åsar* or *osar* as an English singular, as is done by some others, seems hardly justifiable. I have, therefore, adopted the Irish term *esker*, which is not open to these disadvantages, and has already become part of the English language. It will be found in several places in Ireland serving as a name for a village situated on such a chain of gravel hills, *e.g.* near Lucan, Co. Dublin.

Theory of eskers.

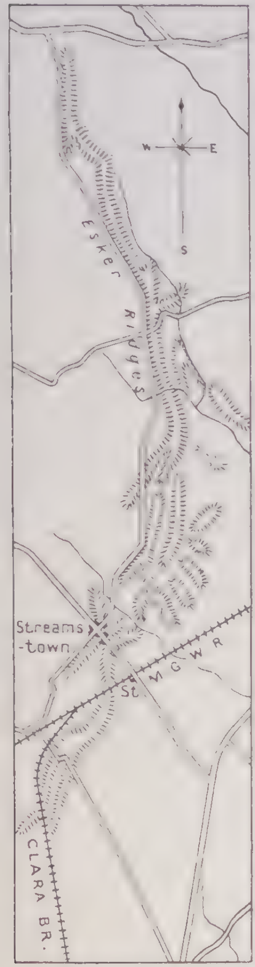

Fig. 20.—Another portion of the same esker.

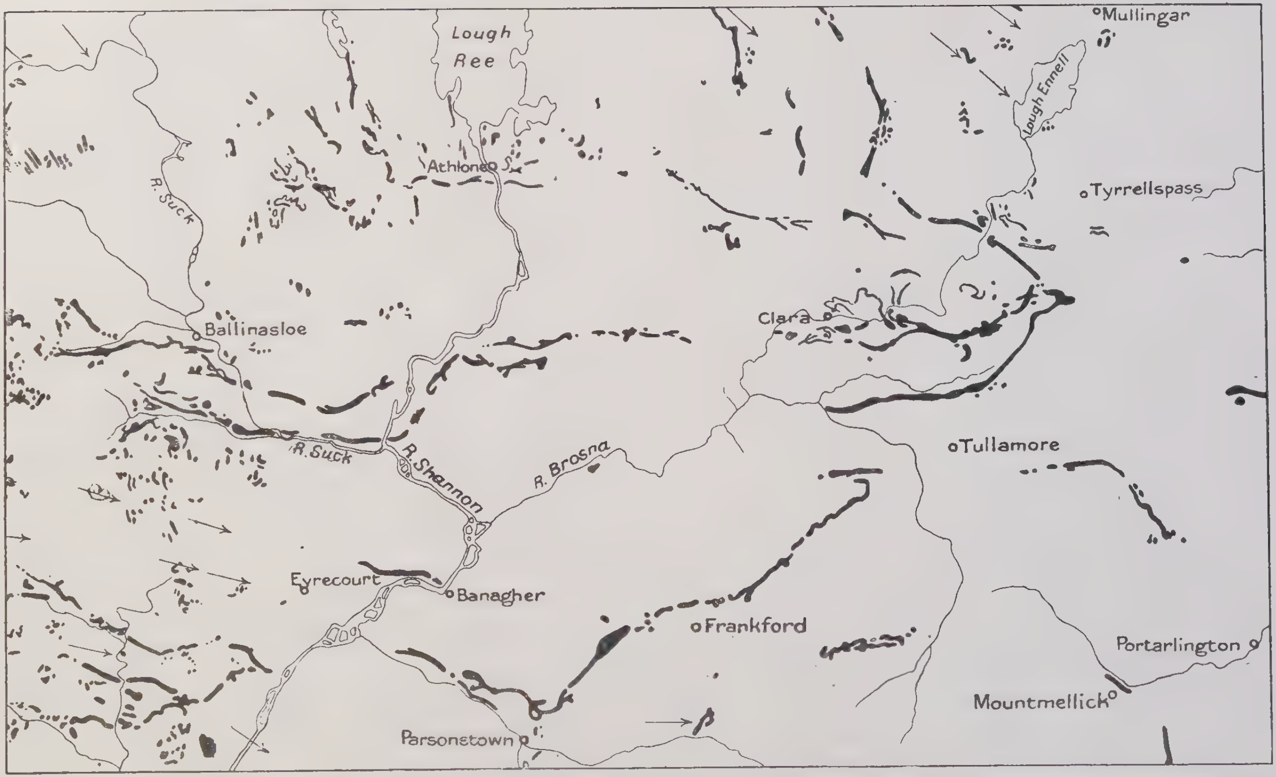

FIG. 21.—Map of portion of the central plain of Ireland, embracing an area about 50 m. × 30 m., and showing the distribution and trend of the eskers. The arrows show the direction of the ice-motion where it is shown by glacial striae, drumlins, or the transport of material. (After Sollas.)

their flanks having been brought there by the falling in of the sides of the channels. Personally, however, I am inclined to the opinion that the essential condition for the formation of eskers is the presence of stagnant water in front of the ice-sheet during its retreat, each mound of the chain being a sort of delta formed by the retreating mouth of the sub-glacial stream. The mouth of the stream lay generally beneath the surface of the ponded water. To this and to the fact that the orifice was on the whole continually retreating and starting a new mound is due the rarity of the typical flat topped form characteristic of the deltas of ordinary streams. The occurrence of flat sand plains here and there interrupting for some distance the course of an esker, which is renewed again in its typical form on the far side of them, is suggestive of the temporary lowering of the level of the ponded water so that deposition could take place up to or above the surface, as well as over a more extended area. In no case, as far as I am aware,

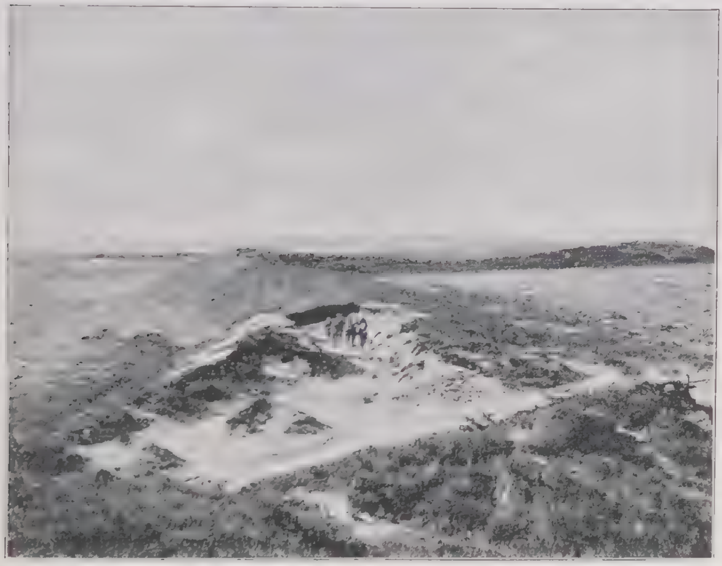

FIG. 22.—Esker ridge at Creggan, 10 miles west of Cookstown, Co. Tyrone.

has a typical esker been found in association with a modern glacier or ice-sheet,[1] a fact which may be correlated with the rarity with which ponded waters are found at their margins. This suggestion as to the origin of eskers must, however, be regarded merely as a working hypothesis, and it may well prove that there are many cases of eskers formed in localities where the ponding of waters by the ice would be an impossibility.

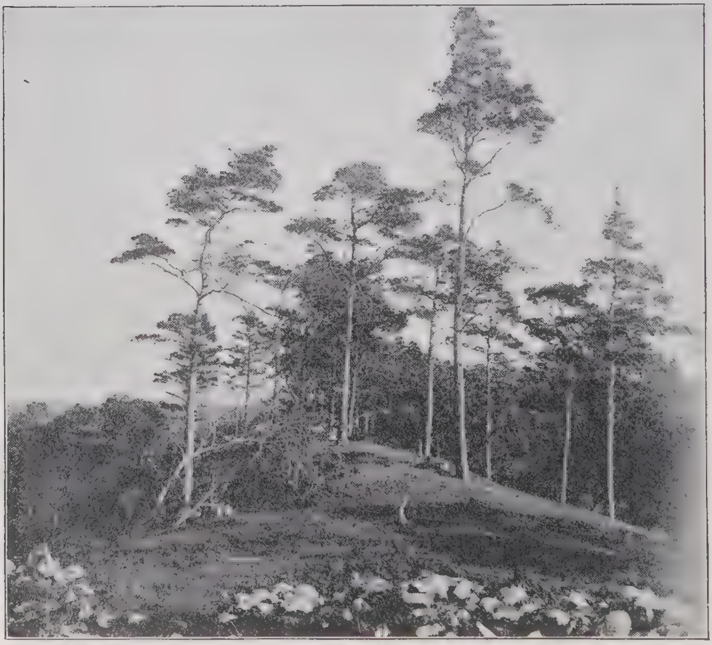

Fig. 23.—Crest of an esker ridge, 4 miles south-west of Tullamore, King's County. This and Fig. 22 from photographs by Prof. Swain.

Relation of eskers to the seasonal clays of the Yoldia Sea.

De Geer has of recent years greatly elaborated this delta theory of eskers. In Sweden the retreating ice margin lay beneath the waters of the late glacial or Yoldia Sea. The postulated conditions were thus in this case fulfilled without any ponding action. Where

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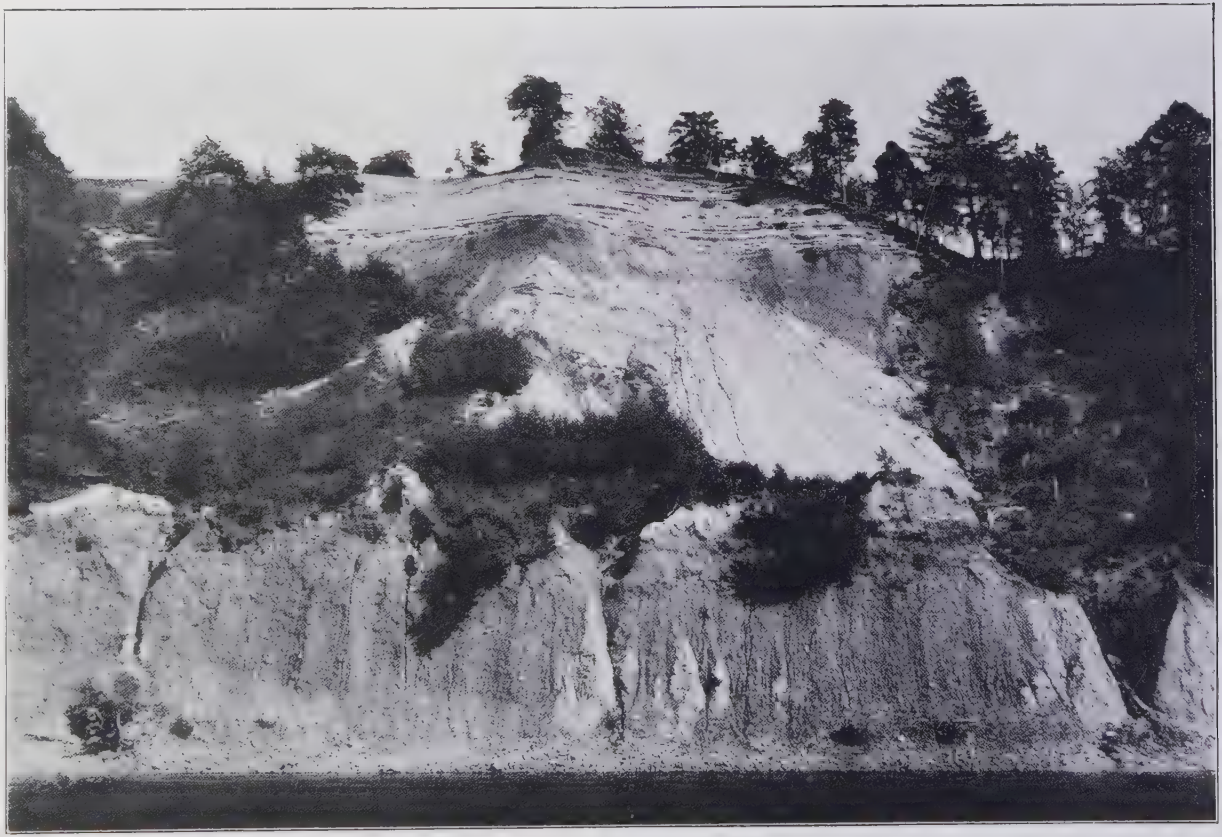
[1] The small ridge of gravel, after which Russell named the esker stream of the Malaspina Glacier, has none of the characters of a true esker, and appears to be merely a product of erosion.



SECTION OF GLACIAL SAND AND GRAVEL RESTING ON BOULDER CLAY, ON THE RIVER SPEY, OPPOSITE ROTHES, BANFFSHIRE, SCOTLAND.

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland.

To face p. 43.

the overburdened sub-glacial rivers opened into the marginal glacier vaults, their transporting power was at once diminished and they began to lay down their burden of sediment. The larger boulders and all the coarser materials were deposited in the innermost proximal part of the vault, the finer gravel and sand carried further out, and the silt borne away to be deposited as the laminated clays which cover the country wherever the late glacial sea extended. Each esker centre, in this way, corresponds with one of the laminae of the late glacial marine clays (see Chap. XV.); and, just as these laminae are to be regarded as marking the seasonal variation of temperature, so every esker centre must be considered as a summer delta formed at the retreating mouth of the glacier river. Each annual layer is spread out like a fan round the esker centre, which forms, so to speak, its handle. As every successive summer in general entailed a retreat of the ice margin, the whole series of these fans lie like tiles one above the other, the uppermost of any pair having its northern or proximal border extending just as far over that of the underlying one as the ice margin had retreated during the preceding year. With the regular recession of the ice margin the handles of the fans became combined into a ridge or chain of mounds, each of which is thus to be regarded as marking a yearly interval.[1]

Gravels interstratified with the boulder-clay.

The widespread intercalation of gravel, sand, and laminated clay between sheets of boulder-clay has led in the past to many erroneous conclusions regarding the retreat and advance of the ice and the occurrence of interglacial periods. So commonly do sections of the drifts show the succession (1) upper boulder-clay, (2) middle sands, (3) lower boulder-clay, that the idea became prevalent that these subdivisions had a stratigraphical significance, and could be correlated from one locality to another. In many instances, however, it is almost certain that the upper boulder-clay is merely englacial moraine, which, on the final decay of the ice, settled down on top of subglacially formed gravels. In other instances subglacial gravels may have been covered over with true ground-moraine by a change or renewal of the motion of the glacier, without having ever been left uncovered by the ice. In either of these cases there is no question of a retreat of the ice margin, and certainly none of an interglacial period. Where, however, the deposits of gravel, sand, and silt are very extensive, or where horizontality of bedding is maintained over large areas, then there is undoubted difficulty in regarding them as of subglacial origin, and it is necessary to postulate a readvance of the ice to account for the superposition of the overlying boulder-clay. Whether such readvance is to be regarded as of interglacial importance must be decided according to local circumstances.

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[1] G. De Geer, "A Geochronology of the last 12,000 years," Geological Congress, 1910.

Marginal gravels.

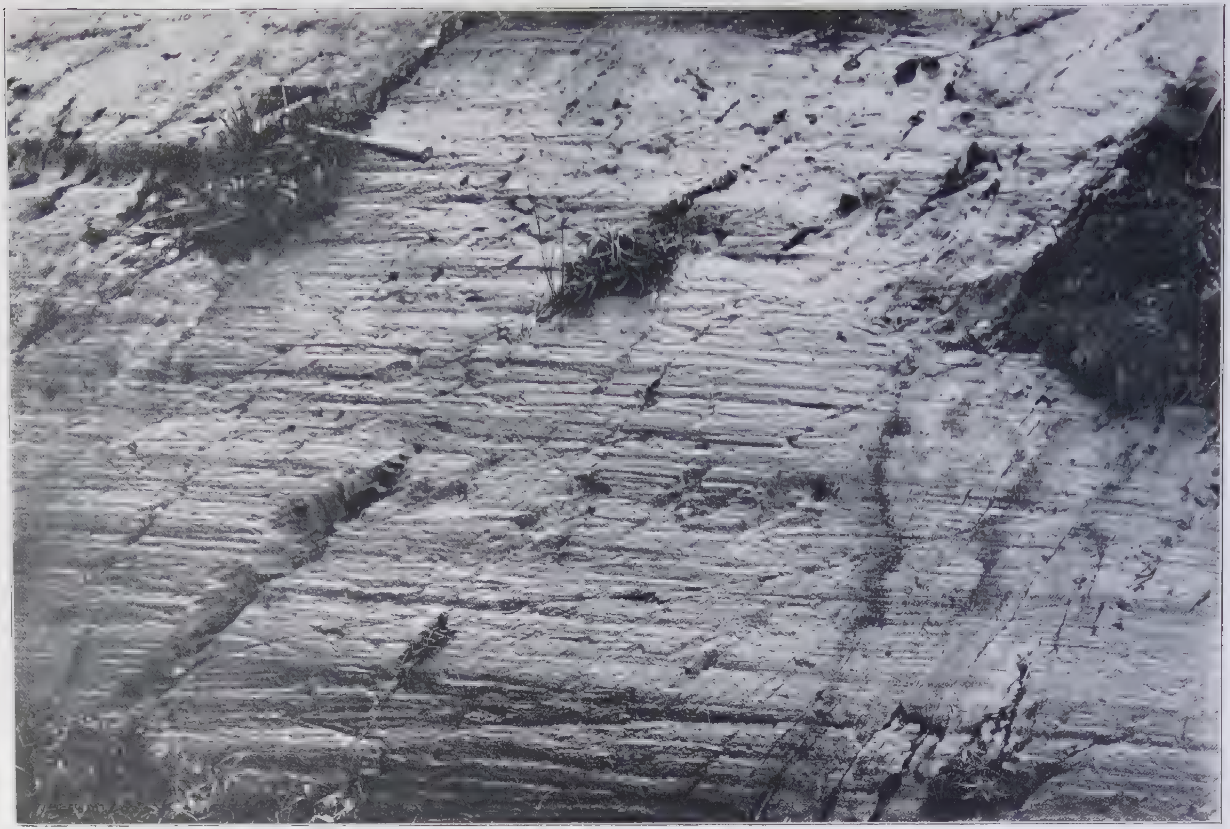
Where an ice-sheet has abutted against a hill slope extensive gravel deposits are frequently found. These have generally a moundy form, and when traced towards the lower ground appear to be continuous with the subglacial gravels which underlie the upper boulder-clay. They have no doubt been laid down by marginal drainage waters, and in many cases bear definite relations to the glacial drainage channels cut by these waters.

Striation and ice-moulding.

One of the most remarkable records left by the passage of ice is the moulding, polishing, and striation of the underlying rocks. This has been effected by grit and stones embedded in the sole of the glacier or ice-sheet and thus dragged along over the rock surface. Where the glaciation has been powerful and the motion persistently in one direction, it has often resulted in the production of immense grooves, and sometimes by the enlargement, at one side, of one of these grooves an undercut face may be produced. In this way the most elaborate fluting is sometimes developed which bears a remarkable resemblance to complicated carving and moulding.

Frequently on a single rock surface two sets of striae can be observed, one of which crosses the other at an

PLATE VII.



STRIATED ROCK-SURFACE AT KILCHIARAN IN ISLAY, ON THE WEST OF SCOTLAND.

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland.

To face p. 44.

Roches moutonnées.

Ice-moulded knobs of rock of the type mentioned above are generally known by the French term *roches moutonnées*. They vary considerably in character, the variations mainly affecting the down-stream or lee side. The up-stream side is generally smoothed away at a gentle angle, but the down-stream side may be rugged and unstriated, steep but still ice-moulded, or smoothed off at nearly as gentle an angle as the up-stream side. Harker draws a distinction between the *roches moutonnées* in the mountain and sub-montane districts in Skye, those in the mountain district being smoothed off on both sides, and those in the sub-montane district having the down-stream side steep and rugged. I am not aware that this relation has been recorded elsewhere.

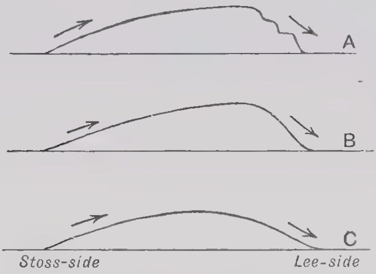


Fig. 25.—Diagram of different forms assumed by *roches moutonnées*. A, Lee-side plucked; B and C, Lee-side moulded.

The occurrence of *roches moutonnées* is largely confined to mountain regions. More common in the lowlands is the phenomenon of *crag-and-tail*. Just as in a modern stream sand and gravel accumulate in the lee of a boulder, so any prominent rock-knob rising in the path of the ice serves as a shelter behind which the glacial drifts accumulate in a long tail, which descends gradually to the ordinary level of the drift plain. The case of the Castle Rock in Edinburgh is a noted example, the High Street extending east from the Castle along the gently descending tail of drift.

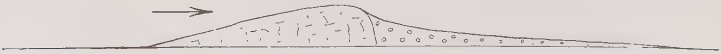
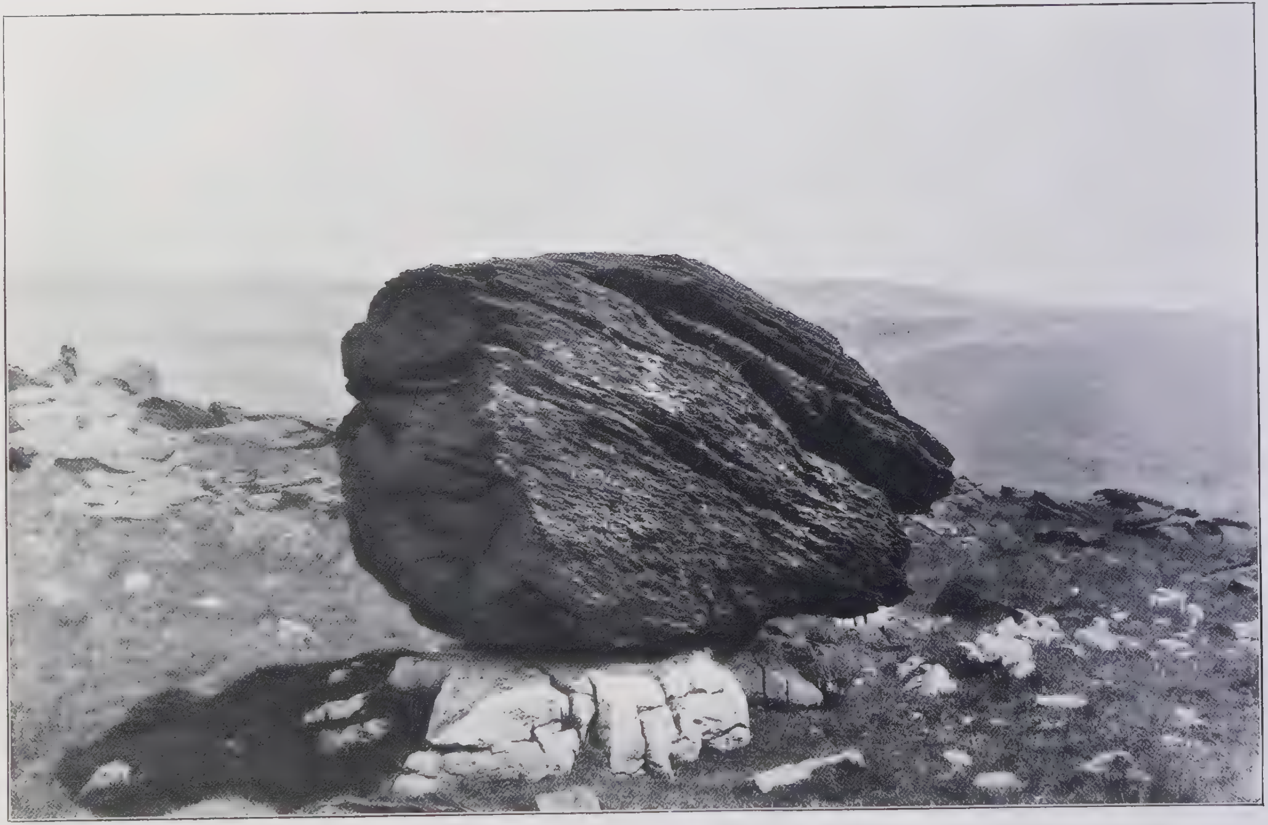


Fig. 26.—Diagram showing the phenomenon of crag and tail, the arrow giving the direction of ice-motion.

PLATE VIII.



PERCHED BOULDER OF SILURIAN GRIT RESTING ON CARBONIFEROUS LIMESTONE, NORBER, NEAR CLAPHAM, YORKSHIRE.

From a photograph by Godfrey Bingley.

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CHAPTER III

THE GLACIATION OF THE BRITISH ISLES

The ice-cap of the Scottish Highlands and the other centres of distribution—The Clyde and Forth Glaciers and the subsequent course of the latter—The central valley of Scotland—The Irish Sea basin—The crossing of the Pennines by the western ice—Evidence of the presence of the Scandinavian ice—The Irish Sea and East Anglian Glaciers—Terminal fanning—The shelly boulder-clay of the Irish Sea Glacier—Distribution of the eurite of Ailsa Craig and of the Galloway and Lake District rocks as erratics—Ice-motion along the Atlantic margin—The Donegal, Connemara, and Kerry centres—Oscillation and overlapping of ice-flows—Ayrshire, Antrim, Dublin, Wexford, east coast of England, Yorkshire, and Lincoln—The Great Chalky Boulder-clay of East Anglia—Westward shifting of the centres of glaciation—Relation of glaciation on east and west sides of Great Britain—Glacial drainage in the Cleveland Hills, Yorkshire—Stages of retreat—Older and newer drift-sheets contrasted—Supposed line separating the older and newer drift—Relation of Palaeolithic man and the Quaternary mammals to the older and newer drift-sheets—The interglacial question—Kirmington—The Cleveland-York line—The Highland Moraine Glaciation.

I

The Ice-cap of the Highlands

Of the many centres of accumulation which nourished the British Ice-sheet, by far the most important, at least in its early stages, must have been that which lay over the Highlands of Scotland. The great range of the Grampians from Cruachan to Cairngorm and the lofty mountains north of the Great Glen, on many of which snow lingers from year to year even at the present day, responded early to the increasing severity of the glacial climate. Glaciers crept out from them on all sides, coalesced into an immense ice-sheet, and finally covered the north of Scotland from shore to shore.

The great focus of supply thus established maintained its dominance throughout the Ice Age in spite of the development of other powerful centres to the south and west. One of these was formed over the Southern Uplands of Scotland, and another still more powerful one over the North and West of Ireland. The mountains of Connemara and Kerry, and those of Wales, Cumberland, and parts of the Pennine Chain, also supported their own ice-sheets, and local caps on the heights of Skye and Mull seem to a large extent, at least, to have enabled these islands to resist the invasion of the main Scottish sheet.

and the other centres of distribution.

The Clyde and Forth Glaciers, and the subsequent course of the latter.

The ice which poured forth from the Highland Glens into the Central Valley of Scotland found itself opposed by that coming north from the Southern Uplands. It split as a consequence into two streams, one of which flowed south along the Firth of Clyde, and the other due east along the Firth of Forth into the North Sea. This latter stream found here a new element of opposition in the presence of the Scandinavian Ice off the eastern shores of Scotland, and again divided into two. One half passed south along the eastern coast of England, and the other north by Aberdeen, merging on the one hand with the Scandinavian flow, and on the other receiving tributary ice from the adjoining land. The united stream swept north-west over Caithness and the Orkneys in the direction of the open Atlantic.

Its power shown by the state of glaciation of the Lowland Valley of Scotland.

It is a striking testimony to the power of the West Scottish Ice that a great part of it found its way to the ocean by this circuitous route in the very teeth of the mighty Scandinavian Ice-sheet. That it was no sluggish stream that swept from west to east across the lowlands of the central valley is proved by the thick drift deposits and intense erosion which characterise this much glaciated area. Between Glasgow and Edinburgh the boulder-clay is in many places moulded into huge drumlins having a west and east trend parallel to the direction of striation and attaining a magnitude seldom equalled in other districts. Further east in the Lothians the solid rock has been ground by the passage of the ice

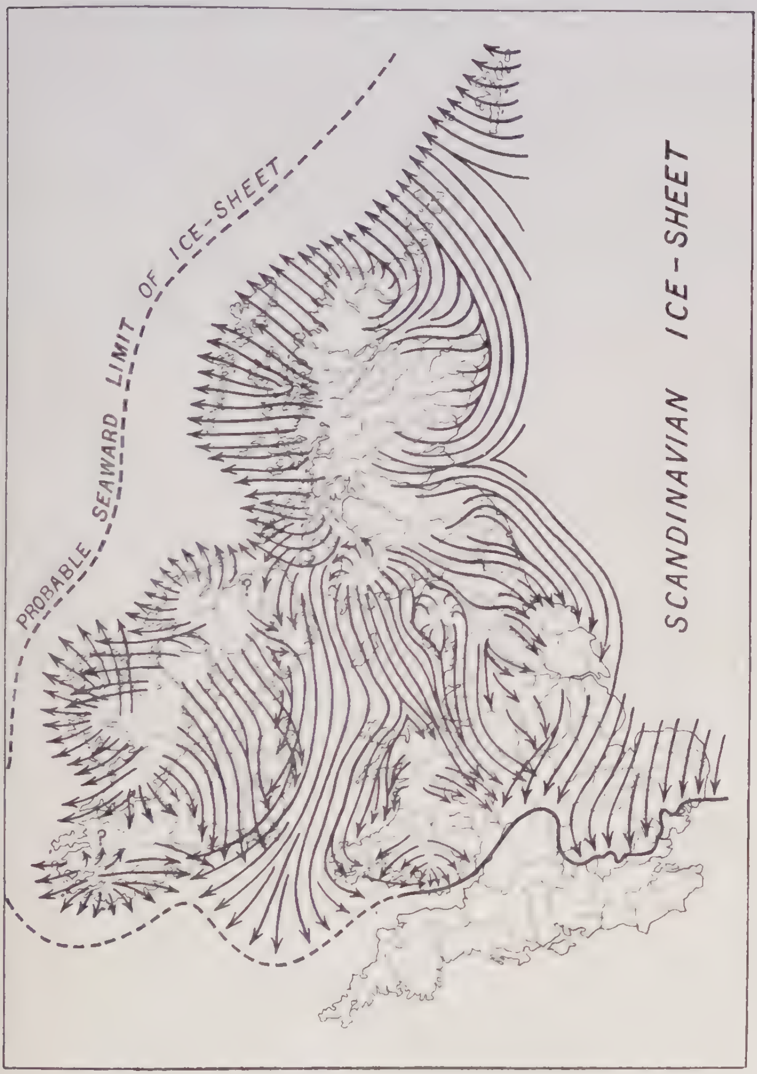

Fig. 27.—Map showing the lines of ice-flow and the limits of glaciation in the British Isles.

into ridges and furrows, which are independent of the structure of the rock, and on such a scale as to create in the mind a vivid conception of the enormous forces involved. The phenomenon of crag and tail is everywhere apparent throughout this district, the case of the Castle Rock in Edinburgh being a familiar example. Anyone who has seen the great furrow which has been ploughed out on the west or up-stream side and on either flank of this crag, and has followed the gently sloping trail of drift which lies away to the east of it beneath the High Street, cannot fail to be impressed with this evidence of the powerful and vigorous action of the ice.

The course of the Clyde glacier.

The great glacier of the Firth of Clyde, the more westerly of the two branches into which the Highland Ice split on coming into conflict with that from the Southern Uplands, impinged upon the coast of Antrim, and was there opposed by the local Irish Sheet. Like its counterpart of the Firth of Forth it here divided its forces, sending one branch west between Islay and Donegal into the Atlantic, and the other south through the North Channel into the basin of the Irish Sea.

The congestion in the Irish Sea basin

This last-mentioned immense but shallow reservoir received contributions of ice from all sides during the Glacial Period. From Wales on the south, from Galloway on the north, from the mountains of Cumberland and Westmoreland on the east, but above all from the great central ice-sheet of Ireland, glaciers poured down into it on every side. A state of congestion was very soon produced and outflow became essential. The whole mass seems to have moved in a south-south-easterly direction over the Isle of Man, on to the northern shores of Wales, forcing back the local ice, and dividing on its flanks into two streams. The lesser of these went south-south-east over the plains of Lancashire and Cheshire into the heart of England; the other, by far the more powerful of the two, swept south along St. George's Channel, and deployed on the shallow sea bottom between Cornwall and Ireland.

and the outflow therefrom.

Meanwhile the congestion in the Irish Sea Basin had a remarkable effect on the glaciers developed in the Lake

District, and in that part of the Southern Uplands immediately north of the Solway Firth. This ice finding its escape to the west barred, turned eastwards into the Vale of Eden, which it soon filled to overflowing, and then poured over the lower passes of the Pennines into the head-waters of the Tyne and Tees (see Fig. 27). Thence it swept down the valleys of these rivers to join the great glacier, which, issuing from the valleys of the Forth and Tweed, crept south along the coast of England. Thus again we find the Western Ice relieving itself by sending glaciers to the east in spite of the presence there of the great Scandinavian land ice. The presence of this ice-sheet off the coast of Great Britain during the Ice Age was long ago established by Croll and James Geikie, and recent investigations have tended to confirm this remarkable fact. South of the mouth of the Tees, all along the shores of Yorkshire are found boulders of undoubted Scandinavian origin. The famous syenite, known as Laurvikite, so widely used as a decorative stone, occurs here in abundance, and also the rhomb porphyries of the Christiania region. These boulders are found not only along the shore, but in the boulder-clay itself, and up to considerable heights on the land, so that any suggestion that they were brought as ballast is quite inadmissible. True, they might have been carried hither on floating ice during the earlier stages of the Glacial Period, and afterwards embedded in the drift. There are, however, the observed deflexions in the outstreaming British glaciers, and these no floating ice could cause. Nothing, for instance, but the presence of land-ice to the east could have sent the powerful glacier of the Moray Firth north-west over the plain of Caithness to deposit there its shell-bearing boulder-clay.[1] Nothing else could have prevented the eastward flowing ice from the Grampians from spreading out on the floor of the North Sea, and sent it creeping north along the coast from Forfar to Aberdeen in the manner its striae and

The crossing of the Pennines by the Western Ice.

Presence of the Scandinavian Ice.

Deflexion of the out-flowing British Glaciers.

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[1] James Croll, "The Boulder-Clay of Caithness a Product of Land Ice," *Geol. Mag.* vol. vii. p. 1 (1870).

the transport of material prove it to have done.[1] From the flow southward along the coast of England we learn a similar lesson. It has been proved beyond a doubt that the southern branch of the great glacier of the Forth went south-east along the coast of Berwick. The Tweed ice turned abruptly south as soon as it rounded the eastern end of the Cheviots. The Tynedale ice went south across the plain of Durham, and that which arrived on the east coast by Stainmoor and the glacier of the Tees took, at least in one stage of its existence, a southerly course along the Vale of York instead of passing out to sea north of the Clevelands. Further south, over Holderness and Lincolnshire, the transport of material proves a general southerly motion with a tendency if anything away from the sea rather than towards it. In its passage across the series of Cretaceous and Jurassic strata which strike north-north-west across Lincolnshire, the ice left a striking record of this southerly or south-south-easterly motion. Here the purple or Hessle boulder-clay which fringes the coastlands outside the chalk-wolds is dragged over the dominantly chalky boulder-clay which crosses the wolds. This latter is dragged south and perhaps somewhat west over the boulder-clay covering the outcrop of the Kimmeridge Clay, and formed largely of it, while this Kimmeridge boulder-clay in turn overlies that which rests on, and is made up of the Oxford Clay to the south-west. Finally, we find the whole of East Anglia covered with an immense sheet of chalky boulder-clay—the Great Chalky Boulder-Clay—which spreads out in a sort of fan around the basin of the Wash, as if deposited by an immense glacier deploying from this centre.

Similar development of the Irish Sea and East Anglian Glaciers.

This great "East Anglian Glacier" and the huge glacier which flowed south along the basin of the Irish Sea—the "Irish Sea Ice" ("West British Ice" of Lamplugh)—formed the main arteries by which discharge took place in the British Isles in a southerly direction towards the zone of melting. The ice which passed north and west towards the Atlantic no doubt reached the margin of the continental shelf, and there breaking off in icebergs floated south with the drift. Both of the two great southward moving streams were confined within narrow limits during a considerable part of their course, the East Anglian Glacier between the Scandinavian Ice and that coming off the shores of England, and the Irish Sea Glacier between the Irish and Welsh Ice-Caps. Both fanned out to an enormous degree when they escaped from this confinement. From this deployment resulted the huge extent of the above-mentioned chalky boulder-clay, which covers some 5000 square miles in central and eastern England. In the centre of the fan lies the basin of the Wash, the largest break in the chalk-wolds of eastern England, and the source, no doubt, of much of the material which went to build up the great drift sheet to the east, south, and west. The fanning of the Irish Sea Glacier is recorded in the distribution of shell-bearing boulder-clay with northern erratics across the south-east of Wexford and along the south coast of Ireland as far as County Cork, and the carriage of similar material over St. David's Head into the Bristol Channel. The ground-moraine of this ice has not as yet been found on the coasts of Devon and Cornwall, but, that it at any rate approached, if it did not override, the Scilly Isles, has been proved by Mr. Barrow,[1] who found erratic material on the northern headlands of these islands.

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[1] T. F. Jamieson, "On the Red Clay of the Aberdeenshire Coast and the Direction of the Ice-movement in that Quarter," *Quart. Journ. Geol. Soc.* vol. xxxviii. p. 160 (1882).

The track of the Irish Sea Glacier is marked by the distribution of the shelly drift,

Wherever the ice of the Irish Sea Glacier invaded the land, it brought with it shelly material derived from the sea bottom. This is to be found distributed over the Mull of Galloway, a great part of Antrim, the lower portions of the Isle of Man, the plain of Lancashire,

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[1] "Geology of the Scilly Isles," *Mem. Geol. Survey.* Mr. Barrow considers that the erratics were brought on floe ice which was thrust up on the land by the pressure of the ice-sheet to the north. As the erratic material has been found at a height of 200 feet one might hazard the conjecture that he was here dealing with actual ground-moraine.

Cheshire, Anglesea, and the coastal districts of North Wales, the coast of Meath, the southern half of County Dublin to the slopes of the Wicklow Mountains, Cardiganshire, and County Wexford. The shells are in nearly all these cases fragmentary, and commonly only the more massive, such as *Cyprina Islandica* and *Turritella terebra*, are preserved. Occasionally glacially striated fragments occur, and in all cases the fragments are associated with erratic material derived from great distances.

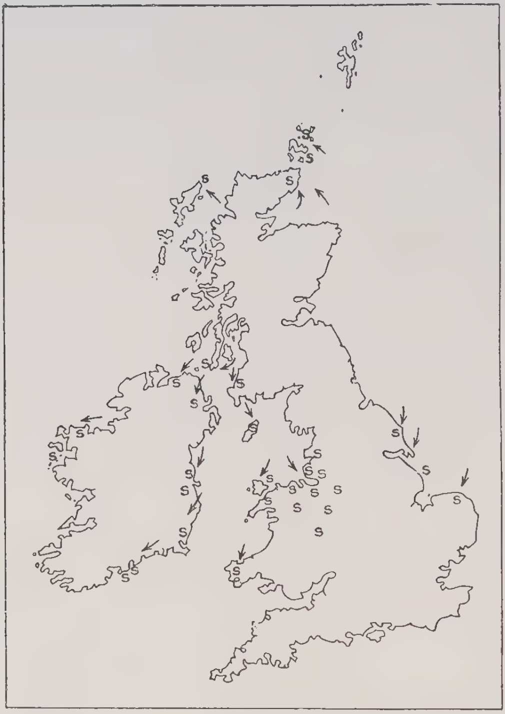

FIG. 28.—Outline map of the British Isles, showing the distribution of the shelly drift (S).

Some of the localities mentioned above show points of special interest. In the Isle of Man the shell-bearing drift is confined to the lower levels. In other cases, however, the shelly drift has been thrust or dragged up to enormous heights on the mountain slopes. The most noted of these is Moel Tryfaen in North Wales. This hill lies to the south of the Menai Straits, being one of the northern foot-hills of the Snowdon Group. The shells occur at an altitude of 1350 feet in well-stratified gravel containing abundant erratic material, including granites from Cumberland and Galloway, and the famous riebeckite-eurite from Ailsa Craig in the Firth of Clyde. The gently inclined drift-covered slopes to the north-east provided an easy track for the ascent of the ice which brought the shells and erratic material, while the presence of Snowdon on the landward side, as Professor Kendall has pointed out,[1] protected Moel Tryfaen from the main force of the Welsh Ice, which had its centre of dispersion further south-east on Arenig Mawr. The gravels arose from the rewashing of the drift by marginal or sub-glacial waters.

which often lies at considerable altitudes.

Some equally famous deposits of high-level shelly drift occur in County Dublin, on the northern slopes of the Wicklow Mountains, and were first described and accounted for by Maxwell Close.[2] The highest of these beds are shelly gravels similar to those of Moel Tryfaen, and occur at various altitudes up to 1200 feet. At lower levels on the Dublin plain to the north, fragments of marine shells have been proved to occur in the boulder-clay.[3]

In Lancashire there is a well-marked inner limit to the area invaded by the Irish Sea Glacier. To the south-west of a line drawn from Carnforth, south-west of Longridge Fell, by Pendle Hill into Burnby, and then up against the western flanks of the Pennines, the drift is charged with debris of marine shells and erratics from the Lake District. To the north-east of this line it contains only local material. Much historical interest attaches to this well-marked line of demarcation, as its existence was one of the most potent arguments which led to the destruction of that geological fiction, the "Great Submergence," to which the drifts were once widely attributed.

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[1] See chapter on the "British Drifts" by P. F. Kendall, in *Man and the Glacial Period*, by G. F. Wright. London, 1893.

[2] "The Elevated Shell-bearing Gravels near Dublin," *Journ. R.G.S.I.* vol. iv. pp. 36-40 (read 1873), 1877; and *Geol. Mag.* (2) vol. i. pp. 193-197 (1874).

[3] See "The Geology of Dublin," *Mem. Geol. Survey of Ireland*, and J. de W. Hinch, "A Contribution to the Glacial Geology of County Dublin," *Irish Naturalist*, vol. xi. p. 229 (1902), in which references to further literature are given.

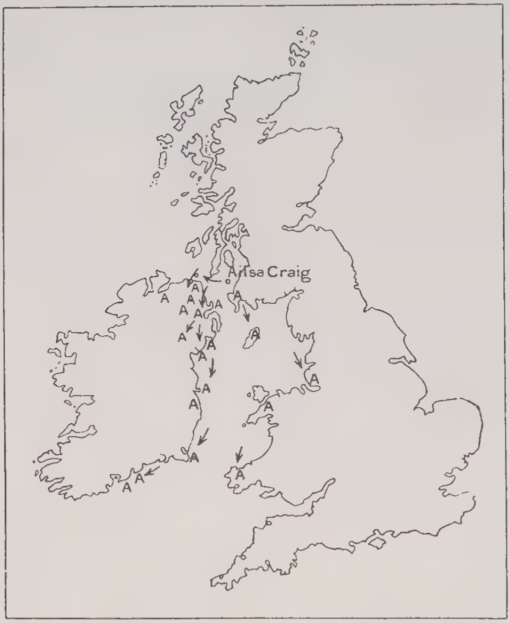

Fig. 29.—Outline Map of the British Isles, showing the known distribution of erratics (A) of the riebeckite-eurite of Ailsa Craig.

The eurite of Ailsa Craig has been widely distributed over the western

The distribution of boulders by the Irish Sea Ice is no less remarkable than that of the unconsolidated shelly deposits which it ploughed out of the bed of the sea. The most easily recognisable of all the erratics borne by this great glacier is the riebeckite-eurite of Ailsa Craig, the blue amphibole of which enables it to be picked out at once from among other fine-grained granitic rocks. The great mass of Ailsa Craig, which rises from the sea halfway between Ayrshire and the Island of Arran, is largely made of this remarkable and, as far as the British

Isles are concerned, almost unique rock. Owing to its position right in the track of the great Clyde glacier, it was carried south in immense quantities into the basin of the Irish Sea, and over a large part of Antrim and Down, where in some localities it is impossible to search half a dozen square yards of ploughed land without finding several fragments of it. It is found in the drifts of the Rhinns of Galloway, the Isle of Man, and Anglesea, and was deposited at a height of 1350 feet on Moel Tryfaen in Carnarvonshire. It occurs also along the coasts of Dublin and Wicklow, and has been picked up as far south as Ballycroneen in County Cork. Throughout its wide area of distribution it is accompanied by the shelly debris so characteristic of the deposits of the Irish Sea Ice.

and the Galloway and Lake District rocks over the eastern part of the area occupied by the Irish Sea Glacier.

Other well-known erratics, the distribution of which has been widely studied, are the granite of Criffel in Galloway, and certain Lake District rocks, such as the Eskdale Granite and the Buttermere and Ennerdale Granophyres. These have been widely spread over the western portions of the area covered by the Irish Sea Ice, and are found abundantly in South Lancashire and Cheshire, and over a considerable area extending south beyond Birmingham. They are also found all along the north coast of Wales and in Anglesea. The most remarkable feature of their distribution, however, is the manner in which they have travelled over the passes of the Pennine Chain to the east coast of England. This course they have taken in company with the well-known Shap Granite, the dispersal of which has been very carefully studied. This granite, which forms Wastdale Crag on the west side of the Vale of Eden, is readily recognisable on account of its remarkably large porphyritic felspars. A few boulders of this rock went north along Edenvale, and a few down Lunedale into Morecambe Bay and thence across Lancashire. The majority, however, crossed the Pennines by the great pass of Stainmoor into the head-waters of the Tees, and travelled thence to the Vale of York and the east coast

The dispersal of Shap Granite

was mainly over the Pennines to the east coast, of England. A few of those which went down the Vale of Eden may have attained the same end by a more circuitous route, joining company near Carlisle with the Criffel Granite boulders and other rocks from the Southern Uplands and northern Lake District, and passing over into the head-waters of the Tyne and Tweed.

but these boulders found no passage south of Stainmoor.

No Shap boulders, however, appear to have crossed the Pennines to the south of Stainmoor. Their southward movement was prevented by the accumulation of a small local ice-cap on Howgill Fells to the south of the Vale of Eden. This local ice-cap, being, like the far more powerful mass to the north, confined on the west by the Irish Sea Ice, sent a tongue through the Pennines by Wensleydale (Uredale) to feed the great glacier of the Vale of York. An eastward flow at Hellifield over the pass between the heads of the Aire and Ribble was also caused by the deflecting action of the Irish Sea Ice. A number of the Yorkshire dales, however, such as Swaledale, Nidderdale, and Wharfedale, received no contribution from the western side of the Pennines, and sent only local ice to feed the Vale of York Glacier. Calderdale, unlike the dales to the north, had no glacier, and contains not a trace of boulder-clay or moraine. Its floor, however, is covered with a great sheet of gravel full of erratics from the western part of the Lake District, which have evidently been washed over the big gap at the head of the valley. These Lake District erratics are entirely absent from the gravels of the valleys tributary to Calderdale.

The western seaboard.

We have up to the present given little attention to the glaciation of the western coasts of Scotland and Ireland. The conditions over this extensive stretch of country, although complex in detail, were on the whole extremely simple. From the Shetlands and Orkneys on the north to the fjords of Kerry on the south, the ice passed seaward along an almost direct route towards the margin of the continental shelf. The reason for this is obvious when we consider the great depths that exist immediately outside the edge of this shelf. Any ice, no matter how thick, pushed forward into these depths must have been immediately broken off into huge bergs and floated away. All factors must have combined to make this continental margin a line of relief towards which the ice currents tended as soon as they had effected their escape from the mountain-bound fjords which characterise these western coasts.

Shetland.

The Shetland Islands, as we have learned from the researches of Drs. Peach and Horne,[1] were completely overwhelmed by the Scandinavian or North Sea Ice, which seems to have crossed the ridges of the island with a curious zig-zag motion rather difficult to understand. The ice appears from the striae to have approached the islands from the north-east, but as soon as it had attained the summit of the eastern ridge it broke away to the north-west, immediately, however, resuming its original course for a short distance before repeating the performance on the western ridge, finally passing out directly north-west towards the continental margin.

Orkney.

The same observers showed that the Orkney Islands were over-ridden by ice which probably originated partly on the mainland of Scotland, and partly in the North Sea, or in Scandinavia, the ice passing over the islands in a north-westerly direction.[2]

Caithness.

Similarly the plain of Caithness is proved by the distribution of the shelly boulder-clay, the final explanation of which we owe to James Croll,[3] to have been traversed by ice from the Moray Firth on its way to the Atlantic margin. Nowhere to the south of this, however, did the North Sea Ice find an avenue of escape towards the Atlantic. In its place we find the ice of the Scottish Hills sweeping out over the relatively low-lying Western

The Western Isles.

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[1] B. N. Peach and John Horne, "The Glaciation of the Shetland Isles," *Quart. Journ. Geol. Soc.* vol. xxxv. p. 778 (1879).

[2] B. N. Peach and John Horne, "The Glaciation of the Orkney Islands," *Quart. Journ. Geol. Soc.* vol. xxxvi. p. 648 (1880).

[3] James Croll, "The Boulder-Clay of Caithness a Product of Land Ice," *Geol. Mag.* vol. vii. p. 1; 1870. See also B. N. Peach and John Horne, "The Glaciation of Caithness," *Proc. Roy. Physical Soc. Edin.*, Session CX. vol. vi. p. 316 (1881).

Isles. The lofty islands of Skye and Mull seem to a certain extent to have resisted invasion from the mainland, staving off the ice to the north and south, and adding their contribution to the general outflow.

Donegal.

The Mountains of Donegal appear to have given rise to a minor centre of dispersion, which formed a sort of off-shoot of the great central axis of dispersion of northern and western Ireland. Owing to its presence the ice motion over Londonderry was deflected towards the north, and this deflection made itself felt as far north as Islay.

Connemara.

Kerry.

To the researches of Maxwell Close and Kinahan we owe our present knowledge regarding the radial dispersion from the mountains of Connemara at the south-western extremity of the Irish axis. Of the conditions in the Kerry and Cork Mountains our knowledge is at present slight. It is, however, pretty clear that the ice moving south across County Clare from the Galway centre split upon the northern flanks of this local ice-cap, the eastern branch passing south into Cork, and the western south-west along the estuary of the Shannon.

Wicklow.

A similar splitting took place on the northern or north-western flank of the Wicklow Mountains, where the south-easterly moving ice from the central axis impinged on the hill slopes. The eastern branch went to feed the great Irish Sea Glacier, while the western joined issue with the ice which passed south over Kildare and Carlow into the counties of Waterford and Wexford.

Areas of fluctuating ice motion.

We have hitherto considered only the distribution and motion of the ice at what we have called the stage of its maximum development. It is clear, however, that there was much fluctuation and, especially along the margins of the coalescing ice-sheets, frequent change in the direction of movement. A certain amount of debatable ground along these margins appears in many cases to have been occupied in turn by ice from different quarters. The record of such changes we find still preserved in areas of cross striae, and the superposition

Oscillation along the margin of the Irish Sea Glacier.

of sheets of boulder-clay, the materials of which have been derived from different sources. Some notable cases occur along the margins of the great Irish Sea Glacier. Thus in Ayrshire broken marine shells are found in the boulder-clay some distance from the sea, and at considerable altitudes, while the striae all indicate motion from land to sea. It is evident that there must have been at some early stage a marked invasion of the coastal parts of this county by ice moving in from the sea, but that later the local ice became dominant. Similarly the south of Antrim appears at some stage earlier than that represented by the main striation to have been invaded by ice moving in from the sea, for broken shells and fragments of the riebeckite-eurite of Ailsa Craig occur far inland near the shores of Lough Neagh. These occur in a chalky boulder-clay which is overlain by a basaltic boulder-clay of more local origin. The plain of Dublin was also invaded in turn by ice from the north-east and north-west. The latter, the local Irish Ice, produced all the striation and the great mass of the boulder-clay which clothes the lower districts, but traces of the shell-bearing ground-moraine of the Irish Sea Glacier can be detected beneath this boulder-clay, and we find in the high level shelly gravels which occur along the northern flanks of the Wicklow Mountains a record of the altitude attained by the margin of this landward moving ice.

The famous "manure gravels" of Wexford, which abound in fragments of marine shells, were also formed at this early stage when the Irish Sea Ice was sufficiently powerful to creep in over the land as soon as it got clear of the Wicklow Mountains, and to spread along the south coast of Ireland as far as Cork. At a later stage ice from the great central plain of Ireland swept south over Wexford and Waterford, while a local sheet diverging from the mountains of the south-west overspread County Cork. Everywhere the striae are due to this later glaciation from the central plain and the mountains of Kerry and Cork, and whenever we see the boulder-clay of this inland ice in contact with the easily recognisable shelly boulder-clay of the Irish Sea Glacier, we find it overlies the latter.

East coast of England.

The best-known and most famous case of oscillation and changing direction of motion is that of the east coast of England. In the opinion of Professor Kendall,[1] the country north of the Cleveland Hills was first occupied by the western ice from Stainmoor Pass and the Valley of the Tees. The Lower Boulder-Clay, the oldest glacial deposit of the district, consists, as was first shown by Mr. Barrow,[2] mainly of the underlying rocks or those outcropping immediately to the west, and the only striae which have been observed beneath this boulder-clay run from north-west to south-east. The Shap Granite which crossed the Pennines mainly on this glacier is dispersed not only along the whole coast-line of Yorkshire, but even far south into Lincolnshire, and at two places, Whitby and Robin Hood's Bay, it has been found *in situ* in the Lower Boulder-Clay. In the last-mentioned locality, 89 boulders of this rock, all of large size, are recorded as having been exposed on the foreshore at one time.[3] How far the Teesdale Glacier extended out to sea at this stage is unknown. A few miles off the mouth of the Tees there is an area of sea bottom known to fishermen as the "Rough Ground." Many of the boulders which cover this area are of Shap Granite, and the belt was interpreted by Carvill Lewis as the moraine of the Teesdale Glacier.

The next phase in the glaciation of North Cleveland was the complete diversion of the Teesdale Glacier south into the Vale of York. This was due to the advent of the great Scottish Northumbrian Glacier which came south along the coast of England. The deflexion may have been initiated by the Scandinavian Ice in the North Sea Basin, but there is no direct proof that this ever actually impinged on this part of the Yorkshire coast. "If it did, its sojourn," according to Professor Kendall, "must have been brief, and the resolution of the conflicting pressures and movements in the area to the northward soon brought in the third element, the Scottish-Northumbrian ice, as a buffer."

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[1] "Glacier-Lakes in the Cleveland Hills," *Quart. Journ. Geol. Soc.* vol. lviii. p. 471 (1902).

[2] *Mem. Geol. Survey*, "North Cleveland," 1888, p. 66.

[3] By Muff and Sheppard, see *Quart. Journ. Geol. Soc.* vol. lviii. p. 564 (1902).

The movement of this northern glacier down the English coast appears to have been long continued and powerful. It brought south along with it immense quantities of erratics of the volcanic rocks of the Cheviots. These occur everywhere right up to the uppermost fringe of the drift on the Cleveland Hills and the Chalk Wolds to the south, and are distributed south into Lincolnshire as far as Horncastle.

Holderness.

In the south of Yorkshire the oscillations of the ice were even still more complex, for here there is abundant proof that the land was actually invaded by the Scandinavian Ice. The splendid cliff sections of Holderness exhibit three well-marked members of the glacial series superposed on one another in the following order:

(3) The Upper Red Clay or Hessle Clay.
(2) The Purple Clay and Stratified Drifts.
(1) The Basement Clay.

The lowest member of the series, the Basement Clay, contains abundant shell fragments and Scandinavian erratics, and was obviously deposited by the Scandinavian or North Sea Ice (East British Ice-Lobe of Lamplugh), at a time when it actually reached the coast of England and pushed up on the land. On it lies the Purple Clay which contains only a few Scandinavian erratics and not many shell fragments, but abounds in boulders of the Shap and Galloway Granites, Borrowdale volcanic rocks and the brockram of Appleby. This clay is bound up in an intimate and complex manner with lenticular sheets of stratified material, the boulder-clay predominating in some localities, and the sand and gravel in others. The stratified phase of this complex middle member of the glacial series has its greatest development on the landward side next the Wolds.

"In the cliff sections of the Holderness plain certain bands of boulder-clay, known as the Upper and Lower Purple Clays, are persistent for many miles; but when the series approaches the rising ground of the Wolds, the individuality of the beds is lost, and they are often replaced entirely by irregular mounds of sand and gravel."[1] The whole of this middle series is suggestive of an oscillating ice-margin stretching along the edge of the Wolds, at one time shrinking and affording space for the accumulation of sand and gravel between the ice and the hills, and again advancing and depositing boulder-clay on top. It is a deposit of the great North Sea Ice-sheet during the period of its waning, when it had already withdrawn from the hill slopes, and left a broad strip on the east coast more or less free from ice. Along this belt subsequently advanced the great Scottish Northumbrian glacier which came south along the coast from the Forth and Tweed, and laid down the Upper or Hessle Clay. The latter is a red clay rich in Magnesian Limestone and in the Old Red Porphyries of the Cheviots, and containing also a few Highland and Southern Upland boulders.

According to the well-matured opinion of Mr. Lamplugh, it was at this stage, when the Pennine and North British Ice advanced southward along the receding flank of the North Sea Lobe, that, as far as the eastern side of England is concerned, the maximum of glaciation was attained, and not at the time of the invasion of the British coasts by the Scandinavian Ice. This great northern glacier, which came south along the coast of England, augmented by the snowfall on its own broad surface, appears to have spread over the lower ground far beyond the bounds of the former invasion, covering most of East Anglia and the East Midland counties with a moving ice-cap beneath which the Chalky boulder-clay was accumulated.[2]

A theory has recently been put forward by Mr.

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[1] G. W. Lamplugh. Pres. Address to Section C of the Brit. Ass., York, 1906.

[2] G. W. Lamplugh, *ibid.* p. 15.

Westward displacement of the centres of dispersion.

Lamplugh to account for these various oscillations and changes in the direction of the ice motion. He is of opinion that the precipitation on the ice-sheets to which they owed their inordinate growth, was due to the moisture-bearing Atlantic winds, and that as the ice grew around the westward centres it interrupted this precipitation, and cut it off from the centres behind. "As the plateaus of ice rose higher in the path of the moisture-laden air-currents they must have gained increased effectiveness as condensers, thereby not only augmenting the snowfall in one quarter, but also diminishing the precipitation in the region to leeward."[1] Thus the ice-sheet of the North Sea Basin attained its maximum development before those of North Britain, and we have as a consequence the Hessle Clay overlying the Purple and Basement Clays on the Yorkshire coasts. The great Irish Sea Ice attained its maximum before that of the Central Plain of Ireland, and so the shell-bearing drift which it deposited along the coasts of Ireland in Antrim, Dublin, Wexford, and Cork, are overlain by the boulder-clay of the Irish Ice-sheet. We have, however, little conception of the time relations of the glaciation on the eastern and western sides of Great Britain. We do not know whether the Irish Sea Ice attained its maximum before or after the great East Anglian Glacier which deposited the Chalky Boulder-clay and the Hessle Clay. The views of Professor Kendall on this point are suggestive if rather daring. He considers that the obstructing action of the Scandinavian Ice off the mouth of the Firth of Forth caused the greater part of the southward moving Highland Ice to find its way into the Clyde, and thence to the Irish Sea Basin. To this was largely due the extreme congestion in this latter area which led to the escape of the Solway and Edenvale Ice over the passes of the Pennines on to the east coast (see p. 51). To explain the fact that the Teesdale glacier apparently spread at first without obstruction into the basin of the North Sea, he considers the impact of the Scandinavian Ice to have proceeded from north to south, so that the Firth of Forth, which lies 100 miles to the northward of the Tees, must have experienced its effects long before they reached the coast of Yorkshire. It must not be forgotten that a damming back of the Forth Glacier to the extent required for this theory, amounting almost to a reversal of its flow, must have taken place at a relatively early stage of its history, for there is no fact more apparent to those who have worked in the area occupied by this glacier than that its eastward motion during its prime was active and powerful, and quite inconsistent with anything but slight obstruction to the east.

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[1] *Op. cit.* p. 14.

Owing to the uncertainty regarding the relation of the eastern and western ice-sheets, it is difficult to construct maps to represent with any degree of certainty the state of glaciation at a particular stage of the Ice Age. We have a fair idea of the succession of events in different districts, but we cannot as yet accurately correlate one district with another. The maps generally published showing the maximum glaciation of the British Isles are in all probability composite maps of many different maxima. If constructed merely on the basis of the observed striation, the lines of movement very likely represent a rather late phase of the glaciation, but we cannot even in this case assume contemporaneity unless it can be shown that the motion in one district had an obvious influence on that in another.

Glacial drainage.

Some interesting and strikingly significant phenomena connected with the marginal drainage of the ice-sheet during its maximum development and retreat have recently formed the subject of research by Professor Kendall, and those who have come more or less directly under his inspiring influence. In the year 1902 he published his great paper on the glacial lakes of the Cleveland Hills in Yorkshire,[1] and the stimulus thus given to this important subject resulted in the application of similar ideas to other widely separated hill centres in the British Isles. Professor Kendall showed that when the northern ice reached its maximum height on the slopes of the Cleveland Hills it impounded in the valleys a system of lakes, which drained one into the other round the flanks of the hills until free escape for the drainage waters became possible. The channels through which the escaping waters found their way lay

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[1] P. F. Kendall, "A System of Glacier Lakes in the Cleveland Hills," *Quar. Journ. Geol. Soc.* vol. lviii. p. 471 (1902). See also "The Glacier Lakes of Cleveland," *Proc. Yorks. Geol. and Polytec. Soc.* vol. xv. p. 1 (1903).

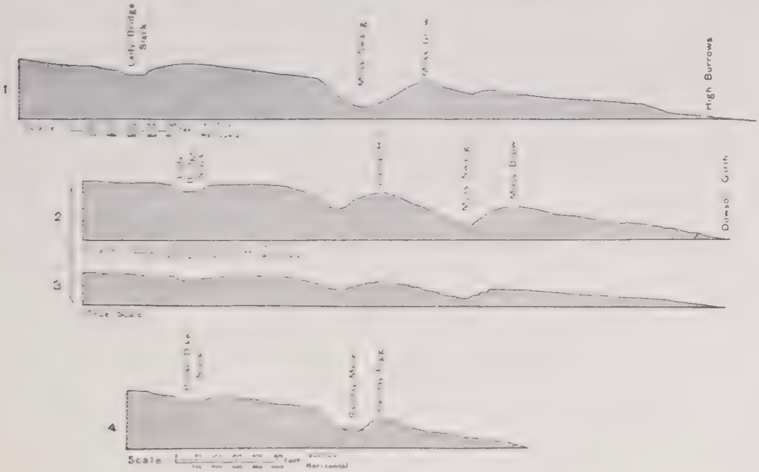


FIG. 30.—Serial sections across the overflow-channels on Murk-Mire Moor. (After Kendall.)

sometimes along the margin of the ice, but often more trenched across some low pass between the valleys. When the ice finally withdrew and the impounded waters could escape at a lower level, these channels were abandoned, and now for the most part appear as dry trenches, catching the eye not only in virtue of their peculiar form, but also because of the impossibility of their formation under present conditions of drainage.

Characteristics of glacial drainage channels.

The independence of the natural drainage is the most striking character of these gorges. They cut through the normal watersheds of the country, and are frequently deepest just where they cross the summit ridges. Such a feature proves that they originated by the passage of water from one side of the ridge to the other, and necessarily implies the action of some impounding agent since removed, which prevented the drainage from taking its normal course. That they are overflows is also borne out by the fact that their gradient is usually very small near the head, but steepens rapidly down stream, a feature seldom observed in normal valleys.

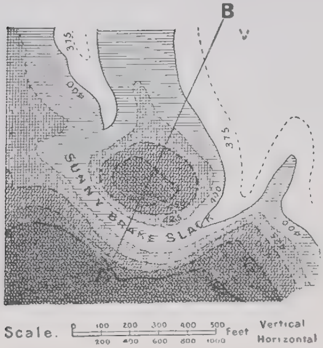

B
375
400
375
400
425
SUNNY BRAKE SLACK
400
A
Scale.
0 100 200 300 400 500 Feet Vertical
200 400 600 800 1000 Horizontal

Fig. 31.—Contour map of Sunny Brake Slack "in-and-out" channel. (After Kendall.)

The outflow channels invariably have steep sides, and, where unmodified by subsequent stream action, broad flat floors. These features are exhibited in their highest perfection in those cases where the valleys have been excavated in very soft rocks, and indicate rapid cutting by a large stream. It is also a noteworthy feature that, where the channels meander, the valley sides are steep on the outer or concave sides of the curves, and gently sloping on the inner or convex sides, a relation which is consistent with the conception of rapid cutting by a powerful stream, too large and active to develop minor meanders on its own valley floor, and so free to exercise constantly its full erosive effect on those portions of the valley sides on which it impinged.

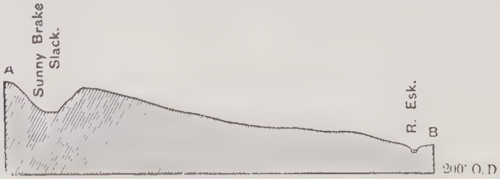


Fig. 32.—Section across Sunny Brake Slack along the line AB in Fig. 31. (After Kendall.)

A carefully contoured map of a typical glacial drainage channel shows many characteristic peculiarities. In ascending such a valley against the stream, so to speak, the sky presently shows through the clear-cut notch of the intake, and the contours, which on the lower slopes simply notch in and cross the gorge bottom as in the case of a normal valley, higher up pass right through the intake, and along the far slopes of the ridge. On these "lakeward" slopes the contours which pass beneath the intake are often, unlike those on the downstream side, quite unindented.

This last character is occasionally repeated at the outfall end of a channel, which in that case opens out inconsequently upon a steep hillside. The level at which this occurs is approximately the level of another lake, into which the stream has discharged its waters, erosion at a lower level being thus prevented.

Four principal types of abandoned channels have been described by Professor Kendall; they are:—

Classification of glacial drainage channels.

(1) Direct overflows:—These trench the main watershed of the country so that the overflow is directly away from the ice. The finest example in the Cleveland Area is Newton Dale. They occupy for the most part the lowest cols, and generally occur singly, one overflow serving for the drainage of a considerable area of the iceward side of the country.

(2) Severed spurs:—This term is applied to those cases where the drainage of minor valleys has been carried across spurs of a main watershed. These occur when a direct outflow across the main watershed is not available, and the waters of the lake then discharge either across a depression of the spurs or by a channel cut on its outer face along the edge of the ice. The former case differs in no essentials from a direct overflow, but the latter constitutes a distinct type (No. 3).

(3) Marginal overflows: –These all start as mere shelves on the hillside, but some develop subsequently into actual gorges. Both marginal overflows and severed spurs often occur in series which may be of two kinds—the aligned sequence and the parallel sequence.

An *aligned sequence* of channels is produced when several valleys are obstructed, and drain from one to another by severed spurs until free escape is offered either laterally or directly. The channels in such a sequence all have their fall in the same direction, and each successive intake, marking an old lake level, must be lower than the one preceding it in the series.

A *parallel* or *successive sequence* results from repeated trenching of the same spur by parallel overflows, produced in succession during the retreat of the ice front. The level at which each overflow occurred initially, before it had effected any cutting, must be lower than the final intake level of its predecessor.

(4) In and out channels:—These are crescentic valleys excavated in the face of a hill by water flowing round a projecting lobe of ice. They form a special type of marginal overflow.

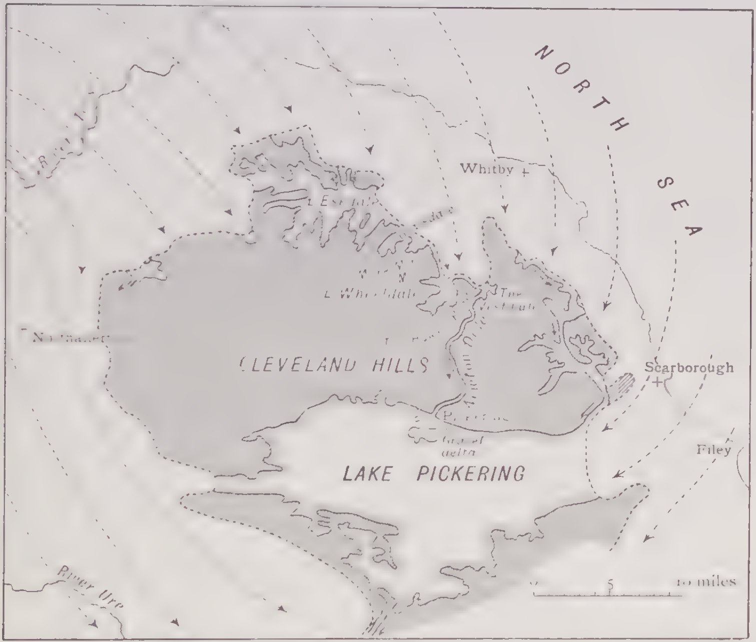
Glacial lakes of the Cleveland Hills.

The conditions which obtained in the Cleveland Hills during the maximum stage of glaciation are represented in Fig. 33, which is constructed from the various maps and diagrams in Professor Kendall's paper. The drainage channels from lake to lake are indicated by the arrows. The conditions along the margin of the Vale of York Glacier are still imperfectly known, Professor Kendall's researches being confined to the northern and eastern flanks of the hills.

An outstanding feature of the area was the immense lake which then existed in the Vale of Pickering. This lake was held up by the ice at both its east and west ends. It received on the north the entire drainage waters of the

Clevelands, for which it acted as a forwarding reservoir, discharging them south through the gorge now occupied by the river Derwent, near Kirkham Abbey.

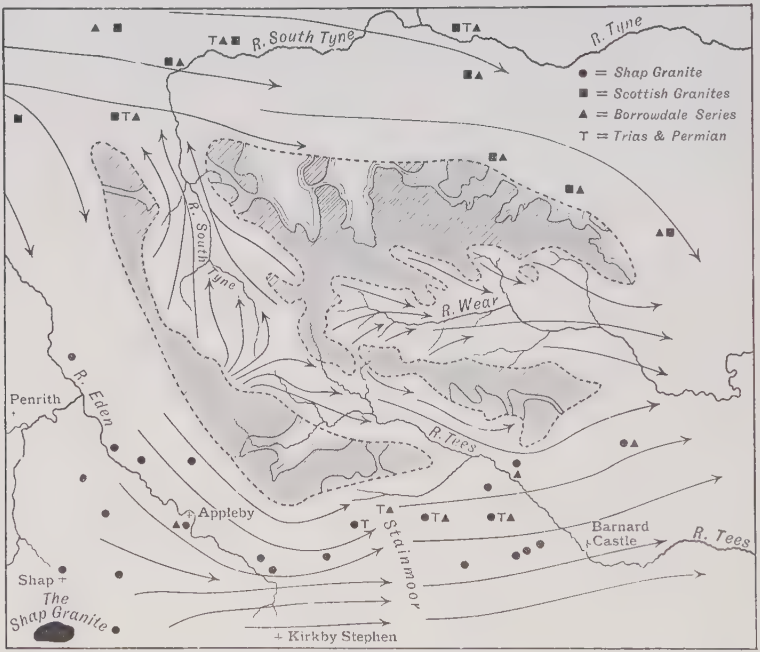
Two main chains of ice-dammed lakes in the Cleveland valleys to the north of Pickering are described by Professor Kendall. These are the Eskdale Series and the Eastern Coastal Series.



Emery Walker sc.

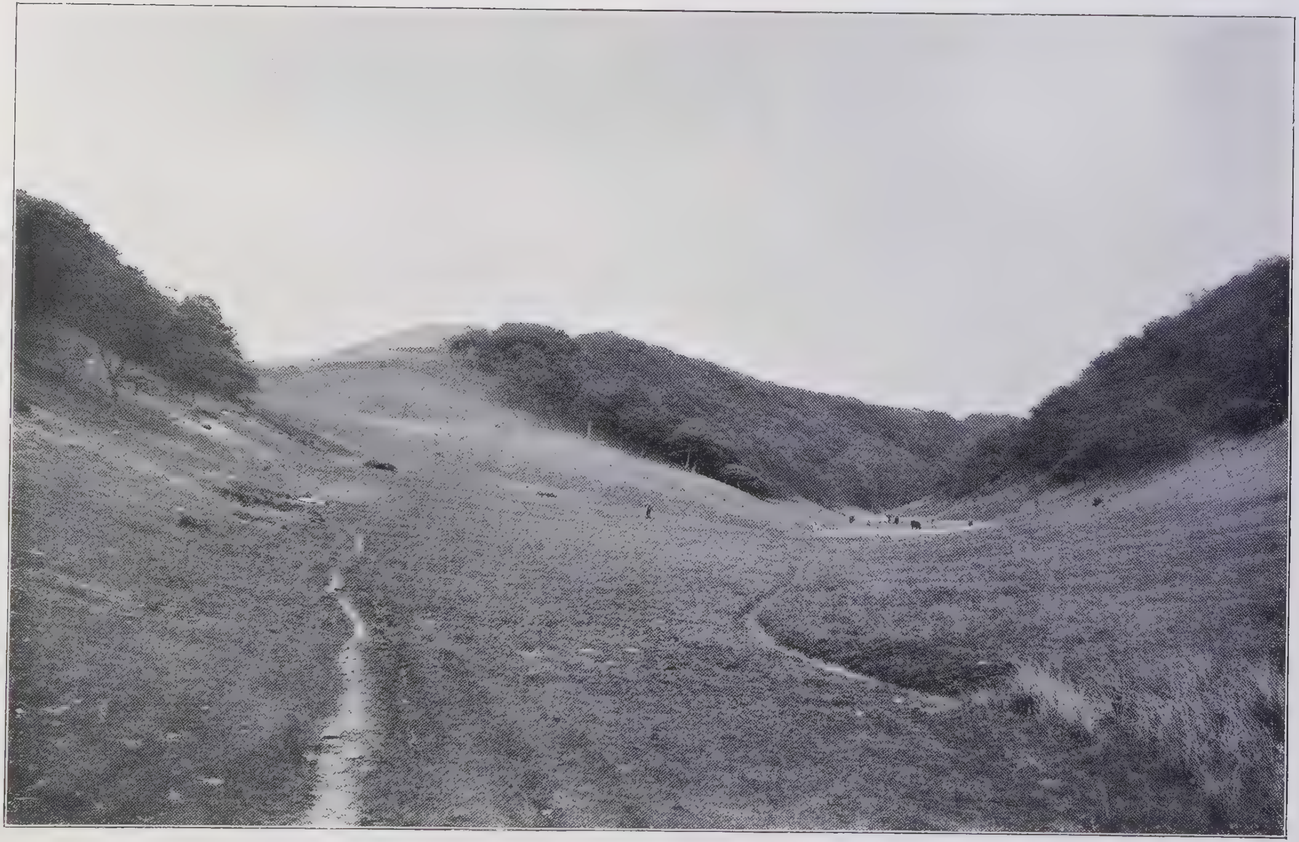
Fig. 33.—Map of the Cleveland Hills, showing the conditions during the supposed maximum extent of the ice. The ice-margin and the ice-dammed lakes after Kendall.

Lake Eskdale, with its continuation Lake Kildale, formed a continuous sheet of water at an altitude of 715′ O.D., held up at both ends like Lake Pickering, by the ice. It received on the north, by direct overflow, the drainage of several minor lakes occupying the recesses in the northern slopes of the Clevelands, and discharged its waters without sensible change of level into Lake Glaisdale. From here the drainage passed by the great trench which cuts across Murk-Mire Moor, and thence by a marginal channel into Lake Wheeldale at an altitude of 670′, forming a gravel delta at its point of discharge into the lake. From Lake Wheeldale it flowed round the bold spur of Two-Howes Rigg by a beautiful marginal channel known as Moss Slack, the intake of which is at exactly the same level (670′) as the outfall of the Murk-Mire Moor channel. It thus reached the little lake known as the Vestibule (525′ O.D.), where the waters were temporarily impounded prior to their discharge southward into Lake Pickering (200′–225′ O.D.) by the great direct overflow of Newton Dale. This splendid overflow channel is 75 feet deep where it trenches the watershed at Fen Bogs, and is at the present day quite devoid of



Emery Walker sc.

FIG. 34.—Map of the glaciers and ice-dammed lakes in the Teesdale, Weardale, and Tynedale areas. The cross-hatched areas are the nunataks or hills which stood out above the ice-sheet during the supposed maximum of the glaciation. The distribution of erratics is also indicated. (In the main after Dwerryhouse.)



RAMMER CLEUGH.

A glacial drainage channel in the Lammermuirs, 5 miles S.S.W. of Dunbar, Scotland (after Kendall and Bailey).

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland any stream for a distance of 2½ miles, its bottom being merely occupied by peat. Where it discharged into Lake Pickering it formed an extensive gravel delta.

Glacial lakes of Teesdale, Weardale, and Tynedale.

A very fine series of glacial lakes in the districts of Teesdale, Weardale, and the Tyne Valley have been described by Dwerryhouse.[1] This district was invaded by ice from the Lake District and the Southern Uplands of Scotland, but considerable portions of the moorland about the head-waters of the above-mentioned valleys stood out as nunataks above the general level of the ice. The upper reaches of the valleys of the Tees, Wear, and South Tyne were occupied by local glaciers tributary to the main ice-sheet.

The principal series of glacial lakes occurred along the southern edge of the South Tyne Glacier. Here at the maximum extent of the ice there was a series of seven or eight lakes draining one into the other in an aligned sequence (see Fig. 34). Other smaller groups and isolated lakes were developed in other parts of the hills. As the ice-margin retreated lower outlets became available, and the lakes shifted their position, and varied in form and number.

Occurrence of glacial lakes in other districts.

Another series of glacial lakes was formed along the south side of the Airedale Glacier in the Bradford and Keighley district, and the northern slopes of the Lammermuir Hills in East Lothian are trenched by a complex system of drainage channels.[2] In the Cheviots similar channels have been found, and they are also to be found along the slopes of many of the mountain ranges in Ireland. They attain a particularly magnificent development along the north and east, and also on the west flank of the Wicklow Mountains. Before leaving the subject reference should be made to the magnificent glacial lakes of Glen Roy and Glen Spean in the west of Scotland, probably formed at a much later period than those of England.

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[1] A. R. Dwerryhouse, "The Glaciation of Teesdale, Weardale, and the Tyne Valley," *Quarterly Journal of the Geological Society of London*, vol. lviii. p. 572 (1902).

[2] Jowett and Muff, "The Glaciation of the Bradford and Keighley District," *Proc. Yorks. Geol. and Polytechnic Soc.* vol. xv. p. 293 (1904); Kendall and Bailey, "The Glaciation of East Lothian south of the Garlton Hills," *Trans. Roy. Soc. Edinburgh*, vol. xlvi. p. 1 (1908).

II

Stages of retreat.

A most absorbing problem, and yet one which in the present state of our knowledge is most difficult to discuss, is that of the relations in space and time of the different stages of retreat of the British Ice-sheets. We can see clearly enough that at different periods the rate of retreat varied greatly, and that marked halts, if not actual readvances of the ice-margin, occurred.

Topography of the older and newer drifts contrasted.

We know, moreover, that there were other differences in the conditions existent during these stages, besides mere variations in the rate of shrinkage. There is, broadly speaking, a marked contrast between the monotonous character of the boulder-clay plains of the south and the infinite variety of kame and esker, drumlin and moraine, associated with the more northerly drift-sheets. There exists, in fact, what the American geologists have termed a difference in the topographic expression of the earlier and later phases of the retreat. In a country of such varied geological structure, with intricately interwoven plain and upland, it is always difficult to unravel effects due to general climatic conditions from such as may be ascribed to differences in topography. Yet, taking all things into consideration, there still remain certain essential differences which cannot be ascribed to local causes. Compare, for example, the central plain of Ireland with that of East Anglia and the Southern Midlands of England. These districts agree in the absence of lofty hills and large valleys, but contrast most strikingly in their minor surface features. We find in the latter case a monotonous sheet of boulder-clay with but little associated gravel, and scarcely any original diversity of surface; in the former an ever-varying range of types. Boulder-clay plains occupy here, as in England, great stretches of country, but they are interrupted by areas of drumlin topography, are strewn over with isolated mounds of gravel and morainic debris, and traversed by innumerable winding eskers.

Greater denudation of the older drifts.

An outstanding point of contrast between the older southern drift and that to the north, which was laid bare at a later stage of the retreat, is the difference in the amount of denudation they have suffered. The southern boulder-clay plains are extensively dissected by a system of valleys, which have for the most part come into existence since the abandonment of the district by the ice. These valleys frequently trench through into the underlying rocks, and the boulder-clay thus comes to occupy the inter-stream areas. When, as for example in Nottinghamshire, the underlying rocks are exceedingly soft and denudation has been especially severe, more extensive removal of the surface has resulted in the drift only remaining as a capping to more or less isolated hills.

Time-interval between the older and newer drifts.

This extensive denudation and maturity of drainage which characterises the older drift is suggestive of a very considerable lapse of time since its exposure to sub-aerial erosion. Moreover, the denudation exhibited by the more northerly drift is trivial in comparison. We might draw from this the conclusion that the interval between the laying bare of the older and newer drifts was immensely longer than post-glacial time, were it not that we have to do with very different climatic conditions in the two periods. There is every reason to believe that the climate of the districts fringing the ancient ice-sheets was of exceptional severity, and that denudation must have proceeded with much greater vigour during the later stages of the Ice Age than under the more temperate conditions of the post-glacial period. It would, in fact, be a great mistake to accept denudation as a measure of time, when we are dealing with such variable relations of temperature and precipitation as appear to characterise the Quaternary.

Boundary between the older and newer drifts.

In the present state of our knowledge it is impossible to draw a definite line separating the older and newer drifts. Large areas can, however, be distinguished as belonging to one sheet or the other. Thus we know that the greater parts of East Anglia and the Midlands of England are occupied by a great dissected sheet of boulder-clay forming part of the earlier drift. This extends north into the counties of Nottingham and Lincoln. On the seaward side of the latter county we have, however, in the Hessle boulder-clay a distinctly newer deposit, which has been traced north along the eastern foot of the Chalk Wolds into Yorkshire. To the west of the Wolds we find the older exceedingly denuded drift, but how far north it extends in the valleys of the Trent and Ouse it is impossible to say, for the country here is largely covered by the Humber warp. North of the city of York, however, we have undoubtedly newer drift. In the west of England we

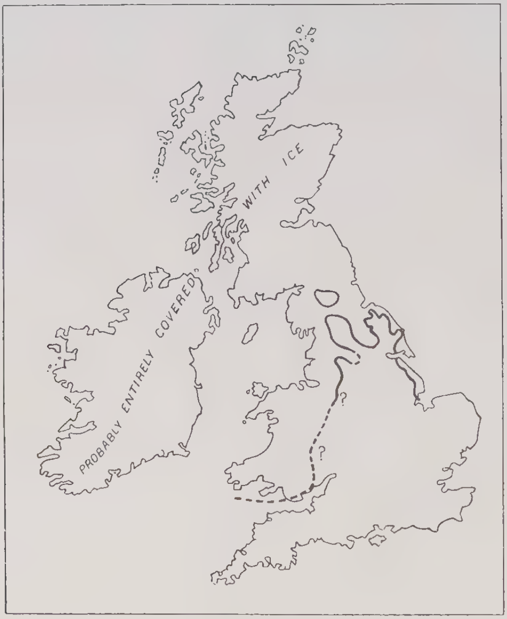

FIG. 35.—Outline map of the British Isles showing the probable limit of the glaciation represented by the newer drift.

know still less about the course of this rather indefinite boundary line. It is probable, however, that parts of Derby, Stafford, and Worcester come within the domain of the older sheet while the plains of Lancashire, Cheshire, and Shropshire, and the greater part of Wales are covered by the newer drift. Indeed, in the west of the British Isles it seems as if the newer drift extends almost as far south as the older, its boundary lying somewhere in the Bristol Channel and passing out to sea to the south of Ireland. We have no evidence that any considerable part of Wales or Ireland was uncovered by ice during what we may call the period of the newer drift.

Occurrence of palaeoliths on the older drift.

Perhaps the most striking testimony to this difference in age is the distribution of the remains of Palaeolithic man. His implements occur in the greatest abundance in the unglaciated parts of the south-east of England. The famous gravels and brick-earths of the Thames Valley have provided them in abundance, and numerous finds have been recorded in many other localities in the southern counties. They are, however, by no means limited to this unglaciated region, but extend some distance in over the boulder-clay sheets to the north. Numerous finds seem to have established beyond question the fact that the implements are in many cases of later date than the glacial drift. The northern limit of the occurrence of Palaeolithic implements is as indefinite, and, at present, as little known as the limit of the older drift. Sir John Evans placed the limit in East Anglia at the Little Ouse. Finds are recorded from Essex, Suffolk, Cambridge, Bedford, Hertford, Buckingham, and Lincoln, all of which are covered in whole or part by the older drift. Moreover, these finds were all in districts in which the newer relatively undenuded drift does not occur, and it may be taken as an established fact that in no single instance has a palaeolith, or any trace of Palaeolithic man, ever been found on the surface within the area of the newer drift. It is, therefore, abundantly clear that

Their absence on the newer drift.

man advanced on to the area left bare by the ice during the first stages of its retreat, but that he failed to follow up this retreat during its later stages when the newer drift became exposed. One finds it difficult to resist the conclusion that he had altogether left the country in the interval, although it is quite another matter to assign a cause for such a general migration. At any rate it is beyond question that in post-glacial times neither Ireland, Wales, nor the northern half of Great Britain were occupied by man until the long subsequent Neolithic invasion. Even the south of England affords evidence of this general exodus, for here there is a complete break both in stratigraphical relations and style of workmanship between the implements of the two periods. Between the Palaeolithic and Neolithic culture of Great Britain there is a great gulf fixed, and no amount of research has succeeded in finding any trace of a transition between the two.

Similar distribution of the Quaternary mammals.

This relation of presence during the initial stages of retreat and absence during its later stages is shared by those contemporaries of Palaeolithic man, the great Quaternary mammals. Remains of the mammoth, the woolly rhinoceros, the musk-ox, etc., abound in the south of England outside the glaciated district, extend up over the older drift, and fail entirely on the surface of the newer drift. The Quaternary fauna no longer occupied the country when the final retreat set in. Its extinction may possibly have been the cause of the migration of the Palaeolithic hunters, who found it difficult to exist in a country devoid of large game. But this is merely to shift the difficulty, not to solve it, for it is as hard or even harder to assign a reason for the local extinction of a whole group of animals than it is to account for the movements of man.

The interglacial question.

We are also as yet in doubt as to whether there occurred anything in the nature of an interglacial period between the periods of the older and newer drifts, which we have just seen to be so distinct from one another. Does the newer drift mark a readvance, and if so how far had the ice-margin retreated before this readvance set in? We have very little evidence in England to suggest an answer to either question. Of the many "interglacial" deposits which have been assigned to such a period only one seems to have stood the test of critical examination. This is the famous shell-bearing clay of Kirmington in North Lincolnshire, investigated by a committee of the British Association.[1] Kirmington lies to the south of the estuary of the Humber, and here at a height of about 100 ft. above sea-level occurs an evenly stratified and undisturbed clay with shells of *Scrobicularia piperita*, *Rissoa ulvae*, *Tellina balthica*, *Cardium edule*, *Mactra subtruncata*, and *Mytilus edulis*, many of them in the position of growth. It is both overlain and underlain by boulder-clay, the overlying boulder-clay being similar to the Hessle Clay of Yorkshire. The fact that the stratigraphical relations are primary and undisturbed may be regarded as established by the carefulness and critical nature of the investigations carried out by the committee appointed to inquire into the matter. The deposits are partly exposed in a brick pit, and the remainder of the section was proved by two borings. The following succession was established:

The Kirmington deposits.

	Ft.	in.
Surface soil (at 95 feet above O.D.) . . .	1	0
Clay with foreign stones (A)	4	0
Well-worn shingle principally of battered flints .	8	0
Laminated warp with estuarine shells, and at its base a thin seam of peat associated with a sandy warp containing freshwater shells in one part of the pit (B)	18	6
Clean yellow sand with pebbles of chalk and flint .	4	9
Red clay passing downwards into tough reddish-brown clay	7	6
Purple clay, streaked with silt and loam, passing downwards into tough purple clay with small stones including some erratics (C) . .	10	6
Carry forward . .	54	3

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[1] *Report of the British Association for 1904*, pp. 272-274. See also G. W. Lamplugh, "British Drifts and the Interglacial Problem" Presidential Address to Section C; *Rep. British Assoc. for 1906*, p. 13.

	Ft.	in.
Brought forward	54	3
Stoneless purple clay	5	0
Stoneless yellow clay	6	0
Flinty gravel	4	6
Yellow clay and loam with small drift pebbles	5	0
Yellow sand, full of well-rounded quartz grains and specks of chalk	8	0
Yellow sand and laminated clay	4	0
Tough compact lead-coloured clay with a few small foreign pebbles (D)	5	3
Tough yellow clay streaked with chalk	1	0
Solid chalk and flint penetrated to	3	0
	96	0

The upper boulder-clay (A) contains, among other erratics, basalt, porphyrite, rhomb-porphyry and grit. It is recognised by the committee as being undoubtedly of glacial origin. In the peaty seam at the base of the shell-bearing estuarine warp (B) some plant remains have been found, all of which, according to Mr. Reid, represent species which occur in neighbouring districts at the present day. The bed (C) is a boulder-clay closely resembling the purple-clay of Holderness, while (D) resembles, and no doubt represents, the basement clay of the same region.

The character and fauna of the estuarine warp show that it must have been laid down between tide-marks, so that the sea-level must, at the time of its deposition, have stood about 70 or 80 feet higher than at the present day. The deposit lies at the margin of the great sheet of drift which covers the lowland to the east of the Wolds. It is not certainly known whether the area west of the Wolds was invaded by ice at the time of the formation of the purple and basement clays. Possibly these clays are contemporaneous with the older highly dissected drift-sheet of western Lincolnshire and Nottingham. The whole question is very obscure. All we can be certain of is that a certain amount of recession of the ice-margin took place between the periods of deposition of the purple and Hessle clays, and that during this period the sea had access to the estuary of the Humber and stood at a somewhat higher level than it does at present.

The position of this section at the margin of the newer drift-sheet is, however, most significant, and it certainly seems to prove that before the maximum extension of the newer ice-sheet there occurred a time when the ice-margin lay somewhat farther north. The extent of this "interglacial" retreat need not have been very great and we have little direct evidence as to its duration. That it was, however, something more than a mere oscillation of the retreating ice-margin seems to be indicated by the marked difference in denudation exhibited by the older and newer drifts.

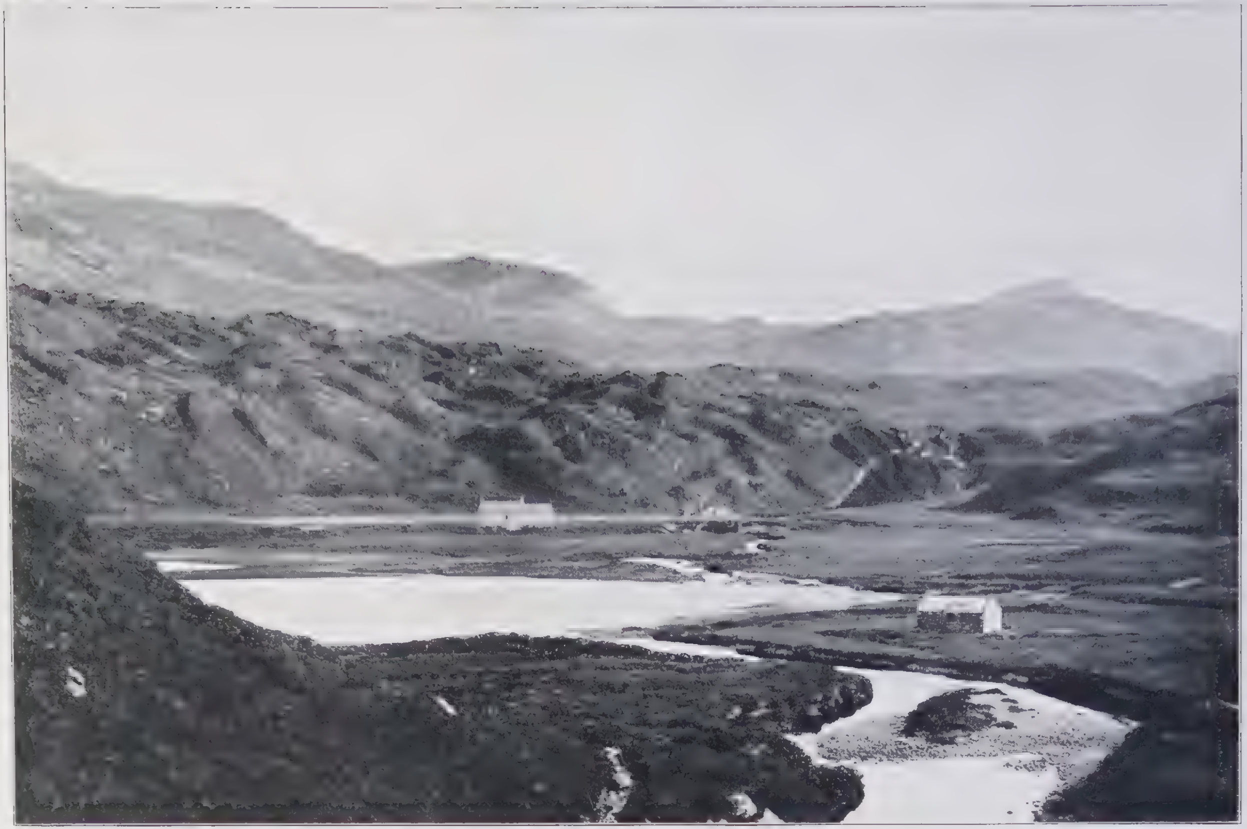
Terminal moraines of the newer drift.

We will now pass on to consider the further stages of the retreat. First, however, it will be necessary to draw attention to the fact that there exist near or at the margin of the newer drift-sheet several well marked end-moraines. One of these forms the southern boundary of the Hessle boulder-clay which covers the sea-board of Lincoln as far south as the shores of the Wash. It is a distinct ridge running out from the high ground of the Wolds into the alluvial flats which here fringe the coast, and is easily visible to any one travelling on the Boston-Mablethorp railway. To the north-east of it extends the Hessle Clay, lapping up against the hills; to the south-west is a sheet of glacial gravel, no doubt of the nature of outwash. The boundary of the Hessle or newer boulder-clay can be traced north from here along the edge of the Wolds across the Humber and round the east and north of the Cleveland Hills. In the valleys and on the slopes of these hills, as for example in the Vale of Pickering and Eskdale, Professor Kendall has described well developed moraines marking the maximum extent of the ice at this stage, and it is worthy of note that the wonderful system of glacial drainage channels which he has described on the northern and eastern side of the Clevelands was initiated at the time of the formation of these moraines. Passing round to the west of the Clevelands we find that at this stage a great lobe of ice extended down the Vale of York, and south of this city there are a couple of well marked moraine-ridges crossing the valley and rising out of the Humber warps, which here cover the greater part of the country. In Airedale and Wharfedale there are also moraines marking the upper limit of glaciation, and a well marked series of glacial drainage channels was initiated, like those of the Clevelands, at this stage. In the west of England we know, as I have said before, very little about the margin of the newer drift.

It must not be imagined, however, that this series of moraines, which we have tentatively correlated with one another, attains anything like the development of those of the Baltic "Höhenrücken" or the great end-moraines of the Wisconsin ice-sheet of America. They are rather to be compared with the much feebler moraines which occur near the margin of the newer drift on the Continent or the Iowan drift of America. It was not until the margin of the British Ice-sheet had retreated to the Highland border that really pronounced moraine formation set in. Here encircling the mouths of the glens and at intervals within them are abundant well marked moraines, producing a type of topography in marked contrast to the smooth or gently rolling plains of boulder-clay a little farther out. This contrast is so striking and the line which separates the moraine-covered district from the boulder-clay plain is in general so clearly defined that many geologists, notably James Geikie, consider that the moraines are the product of a new and distinct glaciation, separated by no inconsiderable interval from that which laid down the boulder-clay. However this may be, it is at any rate obvious that in the moraines we have the record of a distinct phase of the glaciation accompanied by some peculiar conditions previously non-existent.

Morainic glaciation of the Highlands of Scotland.

PLATE X.



THE VALLEY OF THE THOUSAND HILLS, $5\frac{1}{2}$ MILES S.W. OF KINLOCHEWE, ROSS-SHIRE.

In the middle distance are the typical hummocky moraines of the Highland Glaciation.

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland.

To face p. 82.

CHAPTER IV

THE PLIOCENE DEPOSITS OF BRITAIN

Classification of the Crag—Change of climate indicated by its fauna—The Forest-bed Series—Fauna and flora of the Forest-bed—Supposed Quaternary origin of the Straits of Dover.

The Crag of East Anglia shows the approach of glacial conditions.

THE Pliocene deposits of Norfolk, Suffolk, and Essex have a peculiar interest for the glacial geologist, since they indicate in a very striking way the gradual lowering of temperature which affected England before the advent of glacial conditions. The beds consist largely of shelly marine sands, known as "Crag," and freshwater and estuarine clays, and are overlain by the boulder-clay and glacial gravels of the district. Mr. Harmer classifies them as shown in the table on the following page.[1]

The Older Pliocene deposits occupy a very limited area and have suffered much more from denudation than the Newer. Their original area of distribution was, however, probably much greater. The distribution of the Older and Newer Pliocene beds of England and Belgium is shown in Fig. 36.

The change of climate during its deposition.

The fauna of the Older Pliocene deposits and of the Coralline Crag indicates a warm temperate climate. The remainder of the Newer Pliocene yields an increasingly cold temperate fauna, while at the very top there

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[1] F. W. Harmer, "The Pliocene Deposits of the East of England," *Quart. Journ. Geol. Soc.* vol. liv. p. 308, and vol. lvi. p. 705. The species mentioned above as specially characteristic of certain horizons are only locally so. Most of them are species still living, though now, with two exceptions, not in the Anglo-Belgian area.

Its classification.

Newer Pliocene

Cromer Beds (so-called Forest-bed Series) Zone of *Eliphas meridionalis.* (Freshwater and estuarine)	
Weybourn Crag Zone of *Tellina baltica.* (Marine)	
Chillesford Clay and Sand Zone of *Leda oblongoides.* (Estuarine)	
Norwich Crag (Marine)	Upper Division Zone of *Astarte borealis*
	Lower Division Zone of *Mactra subtruncata*
Red Crag (Marine)	Crag of Butley Zone of *Cardium grœnlandicum*
	Crag of Newbourne Zone of *Mactra constricta*
	?
	Crag of Oakley Zone of *Mactra obtruncata*
	Crag of Walton Zone of *Neptunea contraria*
Coralline Crag Zone of *Mactra triangula*	

Older Pliocene

Lenham Beds	Zone of *Arca diluvii*
Boxstone Fauna	

is a freshwater bed with Arctic plants.[1] This gradual change from a warm to a cold temperate fauna is admirably shown by Mr. Harmer in the following table, which also exhibits at a glance the almost equally gradual decrease in the number of extinct species:—

Change of climate shown by a table of species.

ANALYSIS OF THE MOLLUSCAN FAUNA OF THE DIFFERENT HORIZONS OF THE CRAG (CHARACTERISTIC AND ABUNDANT SPECIES ONLY).

	Not known living.	Living only in distant seas.	Southern.	Northern.	Northern and southern.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Weybourn Crag . . .	11	..	..	33	56
Norwich Crag . . .	11	..	7	32	50
Crag of Butley . . .	13	4	13	23	47
Crag of Newbourne . .	32	5	16	11	36
↑ Crag of Walton and Oakley	36	4	20	5	35
Coralline Crag . . .	38	4	26	1	31

The upper members of the series,

A more particular interest attaches to the top member of Mr. Harmer's classification, commonly known as the Cromer Forest-beds. Mr. Reid [2] has shown that this consists of three divisions—an Upper and a Lower Freshwater Bed, and an intermediate estuarine deposit. Between it and the overlying glacial deposits there occur two other beds of doubtful age, known as the Leda Myalis Bed and the Arctic Freshwater Bed. The former Mr. Reid classes provisionally as Pliocene, the latter on account of its Arctic flora he regards as the base of the Pleistocene. We thus have the following preglacial sequence on the coast of Norfolk:—

their classification

Base of the Pleistocene	Arctic Freshwater Bed with *Salix polaris*, *Betula nana*, etc.	
Pliocene	*Leda myalis* Bed (classed provisionally with the Pliocene)	
	Forest-bed Series	Upper Freshwater Bed Estuarine Bed Lower Freshwater Bed

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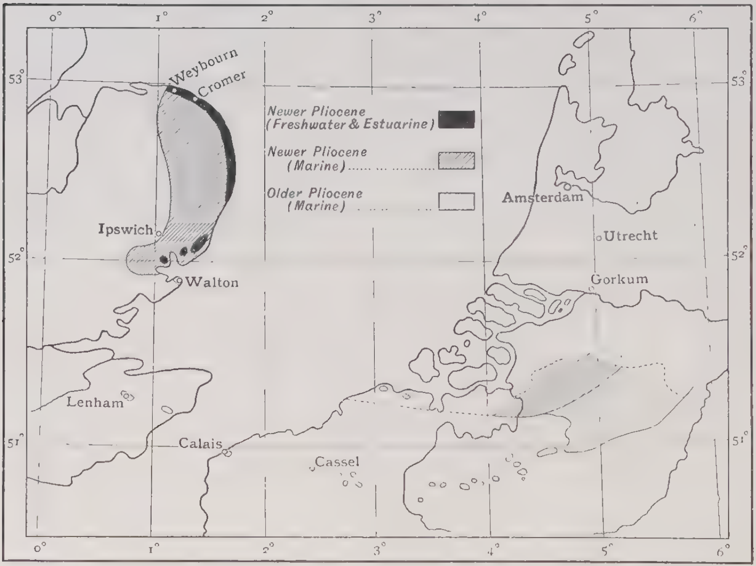
[1] Clement Reid, "Pliocene Deposits of Britain," *Geol. Survey Memoir.*

[2] *Ibid.*

and relation to one another.

The Lower Freshwater Bed is seldom preserved, though its flora is well known from the quantity of *Pholas*-bored cakes of peat and clay-ironstone found in the Estuarine Beds, and derived from the breaking up of the underlying deposit. The relation of the Lower Freshwater Bed to the Estuarine Forest-bed seems to be somewhat similar to that of the recent submerged forests[1] in our estuaries to the deposits now forming in the same localities, in part from their destruction.



Emery Walker sc.

FIG. 36.—Map of the south-east of England and the adjoining parts of Europe, showing the distribution of the Pliocene Deposits. (After Clement Reid.)

The "Forest-bed" an estuarine deposit.

The middle division, which is more particularly the "Forest-bed" of Norfolk geologists, least deserves the name; for wherever it can be studied it is distinctly estuarine, though, from containing large quantities of drift wood, and especially stumps of trees, many have accepted it without hesitation as a land surface. It is from this division that most of the large mammalian remains have been obtained.

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[1] See Chapter XVI.

The upper surface of these Estuarine Beds is in many places weathered into a soil, and penetrated by small roots, on account of which it has come to be known as the "Rootlet Bed." Here and there this surface is covered by lacustrine deposits. These form the Upper Freshwater Bed, in which most of the small bones and freshwater shells are found.

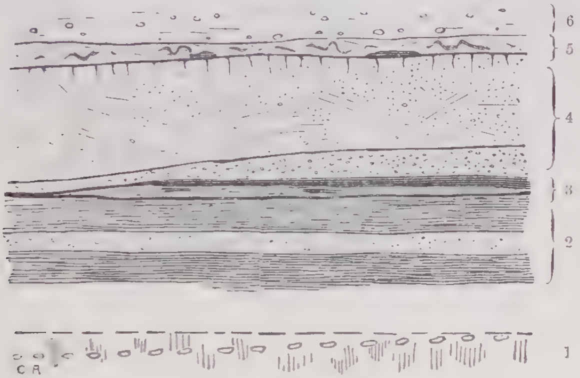

FIG. 37.—Section of the Pliocene Deposits seen in the lower part of the cliff near Trimingham, Norfolk. (After Clement Reid.)

1. Probable position of the chalk. 2. Weybourn Crag (laminated clay and sand). 3. The Lower Freshwater Bed (silt full of seeds overlying laminated lignite and loam). 4. Forest-bed (estuarine beds consisting of sand with the upper part penetrated by rootlets, overlying clay, pebbles, gravel, sand, and lignite with numerous bones). 5. Upper Freshwater Bed (false bedded sand mixed with carbonaceous blue clay). 6. Boulder-clay.

It will be seen that though a land surface does occur in the preglacial deposits, it does not correspond with the horizon to which the name "Forest-bed" has been more especially applied.[1] The main reason why this "Forest-bed" was for a time accepted as a land surface was the occurrence in it of many large stools of trees, often in an upright position, and occasionally with interlocking roots. That these have merely been drifted into place is evident, however, from the following considerations:—

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[1] *The Pliocene Deposits of Britain*, p. 149.

(1) Where the tree stumps are embedded in clay, the clay is well laminated, undisturbed and unweathered.

(2) The roots do not end in small fibres, but are broken off, generally from 1 to 3 feet from the stem, and the ends are either rounded or frayed out.

(3) In a few instances, in cavities between the roots of stumps but little damaged, remains of peaty loam, such as generally forms the soil in a fir forest, are seen, and yet the matrix in which these stools were embedded was laminated clay.

(4) A large number of the stumps are lopsided, that is, have the roots all on one side, as would be the case with trees growing out of a steep river bank and hence liable to be washed away.

(5) Some stools have the bark worn off in exposed places, while it is preserved in the hollows.

Slight unconformity of the Forest-bed to the Crag below.

One of the most marked features in the stratigraphical relations of the Forest-bed is the eroded surface of the Crag on which it lies. Trial borings have shown that there is always a more or less gravelly base to the Forest-bed, beneath which the Crag is cut into by numerous channels or hollows. No evidence has been detected of any change of climate or variation in the fauna and flora between the periods represented by the Lower and Upper Freshwater Beds. The comparison of the faunas of the Forest-bed and that of the underlying Norwich Crag is difficult owing to one being a marine and the other a freshwater and estuarine deposit. It seems to show, however, that there is no great break between them. Several extinct and several arctic forms of marine mollusca occur in both. We will now proceed to consider the fauna of the Forest-bed and the conclusions that may be drawn from it. The following is a list of the mammals :—

Mammalia of the Forest-bed

The Fauna of the Forest-bed.

Machærodus (Sabre-toothed tiger). Crag, Pleistocene, extinct.
Canis lupus, Linn. (Wolf.) Crag.

Canis vulpes, Linn. (Fox.)
Hyæna crocuta, Erxl. (Spotted hyæna.)
Ursus horribilis, Ord. (= *U. ferox*) ?
—— *spelæus*, Blum. Pleistocene, extinct.
Mustela martes, Linn.
Gulo luscus, Linn. (Glutton.) Now exclusively northern.
Lutra vulgaris, Erxl. ? Crag.
Bison bonasus, Linn.
Ovibos moschatus, Zimm. (Musk-ox.) Now confined to the extreme north of N. America.
Caprovis savinii, Newt. (Species of mouflon.) Extinct.
Capreolus caprea, Gray ?
Alces latifrons, Johnson. Extinct.
Cervus dawkinsi, Newt. Extinct.
—— *elaphus*, Linn.
—— *etueriarum*, Cr. and Job. Extinct.
—— *fitchii*, Gunn. Extinct.
—— *polignacus*, Robert. Extinct.
—— *rectus*, Newt. Extinct.
—— *savinii*, Dawk. Extinct.
—— *sedgwickii*, Falc. Extinct.
—— *tetraceros*, Mackie. Extinct.
—— *verticornis*, Dawk. Extinct.
Hippopotamus amphibius, Linn.
Sus scrofa, Linn. (Boar.)
Equus caballus, Linn. ? Crag.
—— *stenonis*, Cocchi. Crag, extinct.
Rhinoceros etruscus, Falc. Extinct.
—— *megarhinus*, Christol ? Pleistocene, extinct.
Elephas antiquus, Falc. Crag, Pleistocene, extinct.
—— *meridionalis*, Nesti. Crag, extinct.
—— *primigenius*, Blumb. (Mammoth.) Pleistocene, extinct, variety only in Forest-bed.
Arvicola amphibius, Linn. ?
—— *arvalis*, Pallas.
—— *glareolus*, Schreb.
—— *gregalis*, Pallas.
—— *intermedius*, Newt. Crag, extinct.
Scincus vulgaris ? Linn.
Mus sylvaticus, Linn.
Castor fiber, Linn. (Beaver.) Crag.
Trogontherium cuvieri, Owen. (Allied to beaver.) Crag, extinct.
Talpa europæa, Linn. (Mole.)
Sorex vulgaris, Linn.
—— *pygmæus*, Pallas.
Myogale moschata, Linn. (Russian desman.)

Northern species.

The list contains two exclusively northern species, the glutton and the musk-ox, the occurrence of which with the other animals is to be wondered at; the musk-ox indeed more so than the glutton, because the latter belongs to the carnivora, which have generally a great climatic range, and are limited more by want of food, competition, or human agency than by temperature.

The elephants and other large mammals.

Among the large mammals the most abundant and conspicuous are the elephants. *E. meridionalis* and *E. antiquus* are the commonest. Besides these only a few teeth have been found, referable with probability to a variety of the Mammoth (*E. primigenius*). The Mastodon, which is common in the Norwich Crag and underlying strata, has entirely disappeared in the Forest-bed. The endless variety of deer is very remarkable.

Of the 30 large land mammals found in the Forest-bed, only 3 are now living in Britain or have been living there within the historic period, and only 6 still exist in any part of the world. The extinction of the large majority is to be ascribed undoubtedly to the Glacial Period. Most of the forms which failed to survive till Pleistocene times were highly specialised herbivora, which would die out through the gradual change in the vegetation as the climate became colder.

The birds, reptiles, amphibia, and freshwater fishes are, as far as is yet known, all living British species.

The land and freshwater mollusca of the Forest-bed number 59 species, of which 6 are extinct and 5 no longer occur in Britain.

Similarity of the flora to that of the present day.

Remains of 68 species of plants have been obtained by Mr. Reid from the Forest-bed. Two of these, the water-chestnut and the spruce-fir, do not appear to have belonged to the British flora since the glacial period. There is an absence of both Arctic and S. European plants, and the whole association indicates a climate and geographical conditions very similar to those of Norfolk at the present day. The sensitiveness of plants to range of temperature makes them especially trustworthy as indicators of climatic conditions, and renders this conclusion more valuable than any derived from the fauna.

The supposed quaternary origin of the Straits of Dover.

The physical geography of the south-west of England during the formation of the Forest-bed has been the subject of much discussion. It is a very generally accepted view that the Straits of Dover were not then opened, and that the Norfolk Forest-bed formed a portion of the estuarine deposit of the Rhine. In view of the prevalence of this idea, I give a brief summary of the evidence for such an assumption:—

(1) The extensive fauna of the Forest-bed is considered to indicate continental conditions, it not being regarded as probable that an island of the size of Great Britain could support such a number of large mammals.

(2) The temperate character of the flora and of the land and freshwater fauna, which, with the exception of two arctic mammals, contains no northern species, is in striking contrast with the northern character of the marine fauna. The latter contains, in addition to several arctic species of mollusca, cetacea and seals, which point to boreal conditions. This contrast would be explained if the North Sea were only open to the north, so that the renewal of the southern elements of its fauna by immigration would be impossible. The southern fauna would thus soon become exterminated by competition with the continually reinforced northern forms.

(3) The examination of the materials of the gravel of the Forest-bed indicates that they were more probably derived from the south or south-west than from any part of England.

I give these arguments for what they are worth, and leave the reader to draw whatever conclusion he can from them. It is necessary to point out, however, that the opening of the Straits of Dover is a geological revolution of considerable magnitude, such as one might well hesitate to ascribe to the comparatively short period embraced by glacial and post-glacial time.

Above the Forest-bed and below the oldest known glacial deposit of Norfolk occur two beds :—

(2) A freshwater or flood deposit with Arctic plants.
(1) A marine bed characterised by *Leda myalis*.

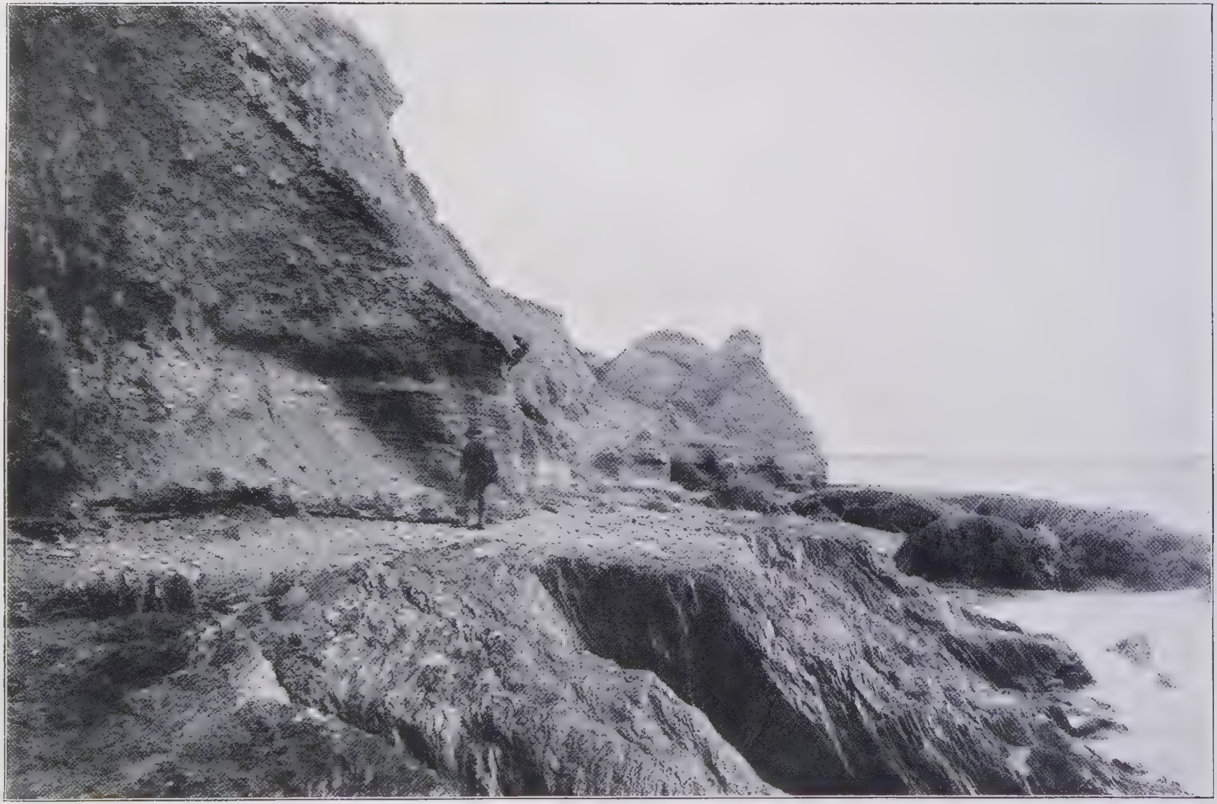
The *Leda myalis* bed.

The lower of these, the *Leda myalis* bed, consists of fine false-bedded loamy sand, only slightly fossiliferous, but containing *Leda myalis*, elsewhere unknown on this side of the Atlantic, *Astarte borealis* and other shells in the position of life, with both valves united. The species mentioned are arctic, but, as the bed seems in other places to contain *Ostrea edulis*, which requires a temperate sea, the evidence is conflicting as to climate.

The Arctic Freshwater bed.

The Arctic Freshwater-bed is a flood loam with arctic plants, including *Salix polaris*, the Arctic Willow, *Betula nana*, the dwarf Birch, and *Hypnum turgescens*, a species of moss. It also yielded *Hippuris vulgaris*, three species of land shells and bones of *Spermophilus*. This fauna and flora though rather meagre is sufficient to show a remarkable change from the climatic conditions of the Forest-bed below. We have here the first indication of the incoming of Arctic *land* species, and their nature is such as to indicate a lowering of temperature of about 20°—a difference as great as that between the South of England and the North Cape at the present day.

PLATE XI.



PLATFORM AND GRAVELS OF THE PREGLACIAL RAISED BEACH IN COURTMACSHERRY BAY, CO. CORK.

There is no head visible in this section, and the gravels of the beach are immediately overlain by boulder-clay.

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CHAPTER V

THE PREGLACIAL RAISED BEACH AND ASSOCIATED DEPOSITS

Raised beach of the south of England—The head or rubble-drift—Its relation to the loess—Preglacial age of the raised beach and head—Yorkshire, South Wales, and Ireland—Elevation of the beach and accumulation of the head—Erratics in the beach gravels—Reversal of present transport of beach material—Harmer's theory of prevalent winds—Distribution and level of the preglacial beach.

The raised beach of Southern England.

ALMOST since the beginnings of the science, geologists have been familiar with the raised beach of the unglaciated parts of the south of England, as it has been repeatedly studied by numerous observers, among whom the names of Mantill, Moore, Austin, Prestwich, and Ussher are prominent. It is a well-marked rock platform about 10 feet above high-water mark, extending at intervals all along the south coast of England from Sussex to Cornwall and right round the Bristol Channel into Wales. Its uniform height over the whole of this coast is one of its most striking features, and we shall see later that it preserves this horizontality over a far wider area. It is almost everywhere overlain by that remarkable deposit, the "head" or "rubble-drift," which rests sometimes on the beach gravel, sometimes on blown sand associated with it, and sometimes directly on the wave-cut rock platform. This is an ancient scree or talus, resulting from the degradation of the old cliff, which marked the inner limit of marine erosion at the time of the formation of the beach. It differs,

The head.

however, from normal scree in several important respects. In the first place it is washed out to a considerably greater distance from the foot of the cliff, and the fragments in it lie at a much lower angle. To such great distances does it extend, that it is sometimes seen capping the raised beach on an island as much as a quarter of a mile out to sea from the preglacial cliff. It has in the second place a remarkably loamy matrix, and contains locally beds or streaks of loam, which give it a stratified appearance. It undoubtedly indicates much severer conditions of climate than are to be found at the present day within the British Isles. What these conditions were we will discuss later.

The coast of France.

Both the raised beach and the overlying rubble-drift occur also all along the coast of France from Calais to Brittany and even farther. At Sangatte near Calais there is a rather important section described by Prestwich. Here the raised beach lies, as before, about 10 feet above the level of the present beach. In the overlying rubble-drift there are beds of loam indistinguishable from loess, and containing land shells similar to those found in the loess. This association with the loess is important, as we shall see later (Chap. X.) that the loess is a dry climate or steppe formation, and the head has many characters analogous to the rubble deposits which form at the margins of the steppes.

Relation of the head to the loess.

In the cliff sections at Blanc Nez the loess can be seen to cap the hills and the rubble-drift to lie in the valleys. According to Prestwich this rubble-drift, which

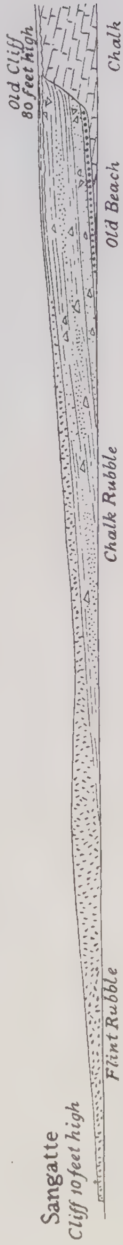

Fig. 38.—Coast section at Sangatte, near Calais, showing the rubble-drift overlying the preglacial beach. (After Prestwich.)

occupies the slopes of the valleys, is identical in every way with the head, which overlies the raised beaches. It seems to take the place of the loess in localities where there is a dominating slope from which talus may be washed down.

This relation of the rubble-drift occurring in the valleys and on the raised beaches, with the loess covering the plateau, is very marked in the Channel Islands. The height of the beach here is said to be less than on the English coast, being only 5 to 8 feet above high tide.

We will now pass from the unglaciated districts of the south to that part of England which was covered by the Pleistocene ice-sheets, and see what relation this beach, and that very remarkable overlying deposit the head, bear to the glacial drifts. Unfortunately, as we pass eastwards towards the Straits of Dover the beach disappears, or at any rate has been removed by the sea in comparatively recent times, and we find no trace of it right up the east coast of England until we come to Yorkshire.

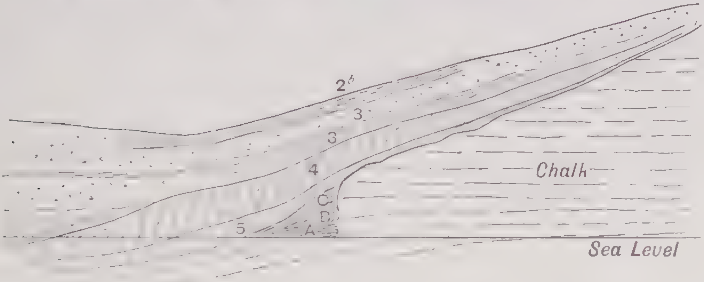

Fig. 39.—Section at Flamborough Head showing the buried cliff and beach deposits beneath the drifts. (After Lamplugh.)

A. Old beach. B. Land wash. C. Blown sand. 5. Chalk rubble. 4. Basement clay. 3. Upper clay. 3b. Intermediate stratified series. 2b. Sewerby gravel.

Preglacial age of the raised beach and head.

Yorkshire.

Here near the village of Sewerby, on the south side of Flamborough Head in Yorkshire, a very remarkable and interesting section has been described by Mr. Lamplugh, in his classical paper on "The Drifts of Flamborough Head."[1] In this section there can be seen emerging from beneath the glacial drifts an old buried sea-cliff of chalk with subtending shore platform, a little above the level of the present shore. On this shore platform and banked up against the cliff in the manner shown in the diagram (Fig. 39) is a succession of very interesting deposits, consisting from below upwards of the following members:—

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[1] *Quart. Journ. Geol. Soc.* vol. xlvii. p. 384 (1891).

(1) An old sea beach of rounded pebbles, chiefly chalk, piled up at the foot of the old sea-cliff to a depth of 4 or 5 feet.

(2) A rain-wash of marly clay and fallen chalk containing land shells and bones, which forms a deposit 5 feet thick on the old beach close under the cliff, but thins out and disappears in less than 7 yards from the cliff.

(3) A thick bed of fine wind-drifted yellow sand, which rests on the rain-wash, or, where that is absent, on the old beach. The cliff behind it is smoothed and rounded by the friction of the wind-driven particles.

(4) A bed of chalky rubble with bands of loam, which covers all the preceding deposits, and can be traced out to sea below low-water mark.

(5) Glacial drifts showing the usual tripartite arrangement of
  (*c*) Upper boulder-clay.
  (*b*) Intermediate stratified series.
  (*a*) Lower or basement boulder-clay.

(6) The Sewerby Gravels, a series of post-glacial gravels formed by the streams which issued from the now dry valleys of the chalk wolds at a time when the ground was frozen and impermeable.

The bed (4) has all the characters of the head of the south coast of England. It lies at the same low angle, extends in the same way to a great distance from the cliff, and contains the same loamy matrix with streaks or beds of loam. Besides, its position, overlying the beach, is identical. There can, therefore, be no doubt that we are here dealing with the same beach, and with the same deposit of rubble as in the unglaciated districts of the south, and we learn here the most important fact that the whole is preglacial.

South Wales.

But we are not dependent on this isolated section alone for the proof that the beach and overlying rubble-drift are preglacial. As we trace them from the unglaciated area of the Bristol Channel along the south coast of Wales to Gower we find that here also, as was proved by Mr. Tiddeman,[1] they pass beneath the glacial drift. Here we get the following section:—

5. Upper head.
4. Boulder-clay.
3. Lower head or rubble-drift.
2. Blown sand.
1. Raised beach gravels.
Wave-cut rock platform.

The deposits rest upon the rock platform, and are banked up against the old preglacial cliff which rises from behind them. It will be noticed at once that there is a new deposit in the series, namely, the "upper head." This is rubble-drift somewhat similar to the lower head, and formed by the degradation of the old cliff, but containing a few subangular and rounded stones derived from the boulder-clay. It is everywhere much thinner than the lower head, but is of interest as showing that the conditions for the formation of the head, which obtained before the advent of the ice, returned for a short period after the ice had melted away.

Ireland.

When we pass farther afield into the south of Ireland we are completely within the glaciated region, the ice having passed right out to sea all along the south and west coast. Yet it is here that we find the preglacial raised beach in its most magnificent development.[1] From Carnsore Point to Cape Clear, at intervals all along the coast, are sections reproducing every essential detail of those at Gower, but far surpassing them in grandeur and perfection of development. Those in Courtmacsherry Bay and at Clonakilty are perhaps the finest. In the former place occurs the section shown diagrammatically in Fig. 40. The succession of the drifts is identical with that of South Wales. The rounded character of the preglacial cliff, brought about by subaerial degradation during the formation of the head, is worth notice, as by its means it is possible to trace the old preglacial coast line even in places where the beach deposits and rock-platform have been removed by the sea.

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[1] R. H. Tiddeman, "On the Age of the Raised Beach of Southern Britain as seen in Gower," *Rep. Brit. Assoc.*, Bradford, 1900.

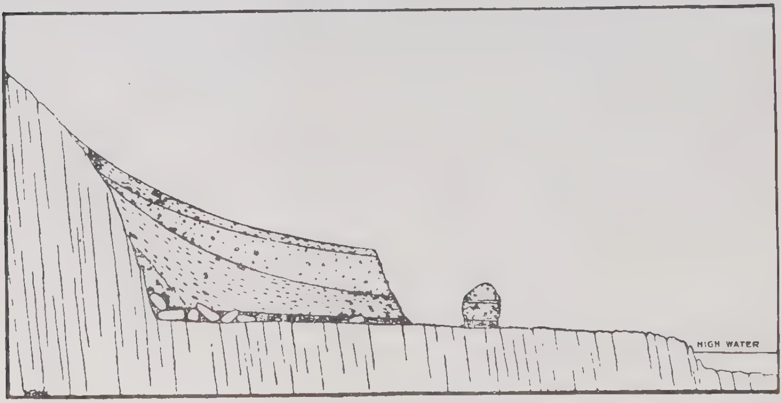

FIG. 40.—Diagram of section of the preglacial raised beach in Courtmacsherry Bay, Co. Cork. (After Wright and Muff.)

1. Raised beach gravel and blocks. 2. Blown sand. 3. Lower head. 4. Boulder-clay. 5. Upper head.

The reader will now have a fairly good idea both of the nature and wide distribution of the phenomena we are discussing, so we will proceed to more general considerations. We have seen that this beach which fringes the shores of Ireland, England, and France is clearly of preglacial age, and the question naturally arises how long before the Ice Age was it formed. It

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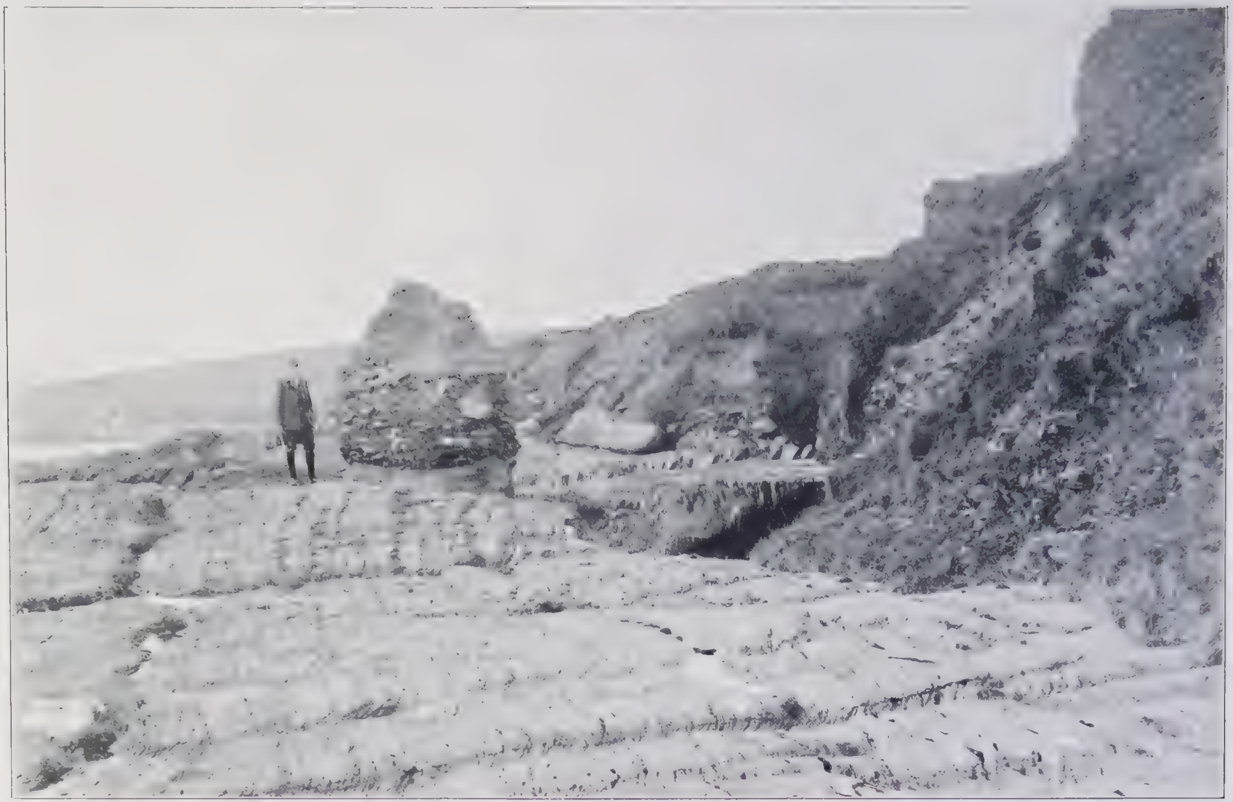
[1] See Wright and Muff, "The Preglacial Raised Beach of the South Coast of Ireland," *Proc. Roy. Dub. Soc.* vol. x. (N.S.) p. 250 (1904).



VIEW OF THE PREGLACIAL RAISED BEACH IN COURTMACSHERRY BAY, CO. CORK.

The deposits overlying the wave-channelled rock platform are attacked at intervals by exceptional storms, so that the platform is now extensively exposed. The section is that shown diagrammatically in Fig. 40, and the corresponding deposits can easily be picked out.

To face p. 98.

must obviously have been raised beyond the reach of the waves some time before the advent of the land ice, or the lower head could not have accumulated on it. The occurrence of blown sand without any great admixture of head close down upon the wave-cut rock platform indicates that this elevation commenced even before the conditions were suitable for the formation of the head. The "land-wash" at Sewerby points to a similar conclusion. Thus we see that between the elevation that put a stop to the cutting of the preglacial shore-platform and the invasion of the country by ice, there was time for the production of land-wash, blown sand, and the head. The first two deposits are of trifling importance as an indication of a lapse of time. A year or two is ample to account for them. With regard to the head, however, one cannot be so sure. It is very hard to put a figure to it. It may represent a very long period of time, and on the other hand it may have been formed very rapidly. It certainly requires more than a couple of years, and I am inclined to suspect that it represents many hundreds.

Elevation of the beach in preglacial times.

There is another line of evidence, however, which bears upon this question of time. We fortunately are able to prove almost beyond a shadow of a doubt, that, during the later stages of the formation of the beach, if the neighbouring land was not glaciated, it was at least subjected to a climate so cold that floating ice could exist as far south as the southern coasts of England and Ireland. There occur in the beach deposits on these coasts, and also in the beaches at Sewerby and Sangatte, numerous far travelled stones, some of such considerable size that their occurrence can only be accounted for by the presence of floating ice. Now, floating ice as far south as this implies the presence of ice-sheets farther north, and means that the Ice Age had already begun. The study of the place of origin of the boulders contained in the beaches along the shores of the English Channel and the south coast of Ireland have revealed a fact of the most exceptional, almost romantic, interest.

Erratics in the beach gravels.

Reversal of present transport of beach material.

The travel of these stones has been entirely from east to west along the coast, contrary both to the prevalent winds of the present day and the tidal drift, such as there is. The strongest and most persistent winds on these coasts blow from the south-west, the travel of the erratics on the beach was from the north-east. It is difficult to resist the conclusion that the winds of those days were in a contrary direction. Mr. Harmer has shown[1] how this might come about. At the present day the main track of the cyclone centres over the British Isles is from south-west to north-east along a line which crosses Scotland a little south of Ben Nevis. The southern shores of England and Ireland are thus crossed by the south-easterly limbs of the cyclones, and the prevalent winds on them blow in consequence from the south-west. If now the track of the cyclones lay farther south, say over Spain and southern France, the British Isles would be crossed instead by their northern limbs and the prevalent winds would be from the north-east. Such a southward shifting of the cyclone track might be brought about by the presence of ice-sheets to the north, say on Scandinavia and perhaps Scotland, which, giving rise to anticyclonic conditions above their surfaces, would effectually displace the track of the cyclones southward. Mr. Harmer devised this theory to account for the formation of the crag deposits on the coast of Norfolk and Suffolk. At present little or no shell sand is being thrown upon these coasts, while an enormous quantity is accumulating on the shores of Holland. A change in the prevalent winds from south-west to north-east would make all the difference and change the area of deposition to the English coasts. Thus it is probable that even during the formation of the Pliocene Crag there were ice-sheets of some importance in existence to the north. This is, of course, all rather speculative. What we can be perfectly sure of, however, is that during the later

Harmer's theory of prevalent winds.

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[1] F. W. Harmer, "The Influence of Winds upon Climate during the Pleistocene Epoch," *Quart. Journ. Geol. Soc.* vol. lvii. p. 405 (1901).

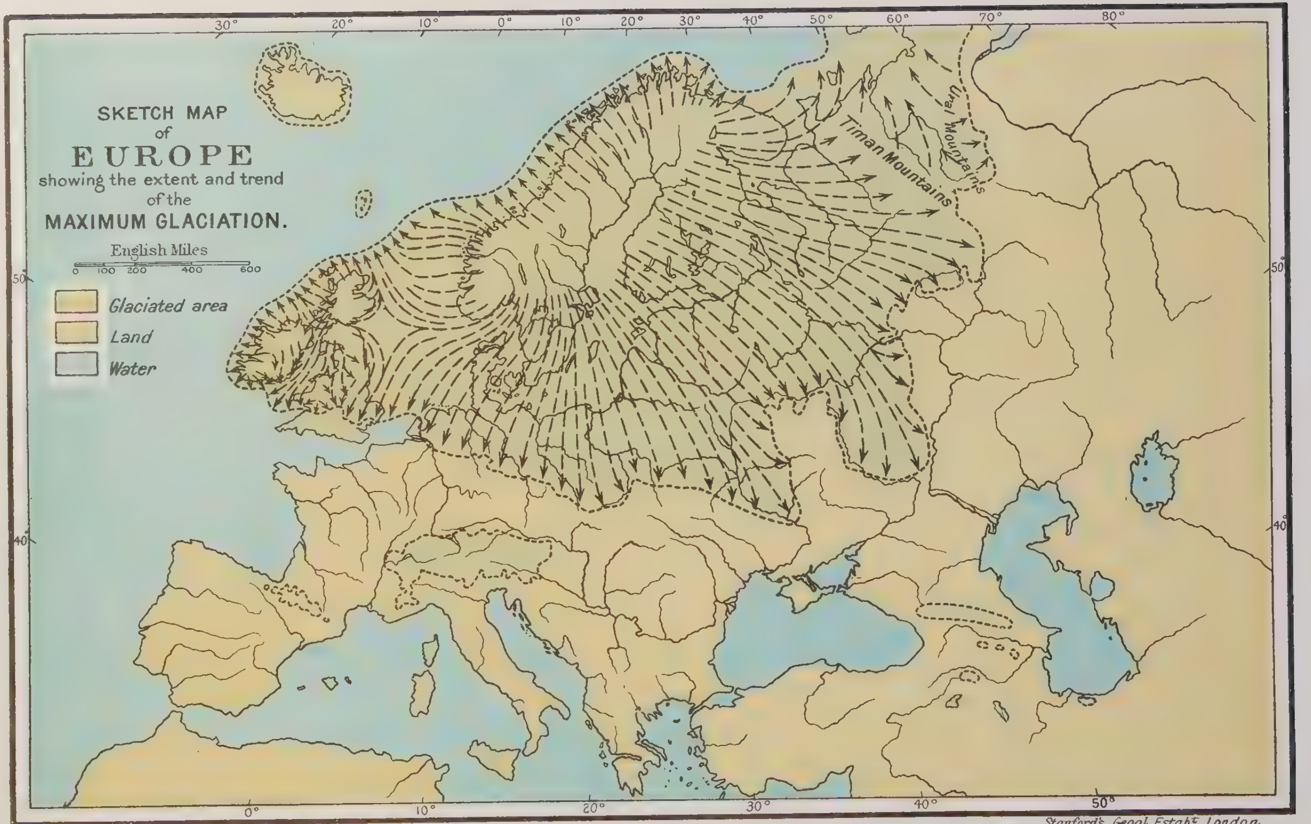
stages of the preglacial beach something approaching glacial conditions of climate affected the south of Great Britain. I say during the later stages, for it is only these we can be certain of having represented in the gravel. The formation of the rock platform may have required an immense period of time, but the gravel on it would be continually resorted and added to, and the erratics may have been introduced only just before the beach was abandoned by the sea.

Distribution and level of the beach.

Let us now consider the distribution and level of the beach. We have seen that it is developed repeatedly over about a thousand miles of coast in England, Ireland, and France. In Yorkshire it has been traced beneath the drifts from Sewerby right across Holderness to the Humber. The old rock platform has been described by Mr. Lamplugh in the Isle of Man, and has also been found on the coasts of Meath, Dublin, Clare and Galway in Ireland. Mr. Fearnsides informs me that it is to be seen on the south coast of Caernarvon, and there is a plane of marine erosion in the island of Colonsay on the west coast of Scotland which was probably formed at this time.

The level is practically constant in all the Irish localities, in the south of England, and in northern France, namely, about 10 feet above the modern shore. In Yorkshire it is a little lower, being only slightly above the present high-water mark. In the Isle of Man it is about the same level as Yorkshire. On the whole, therefore, the level is remarkably constant, there being an appreciable departure from the uniform height of 10 feet only in two localities, and these two localities, though it may be a mere coincidence, lie within the area affected by the movements of which we have a record in the post-glacial raised beaches. Outside this area the beach may be said, for all practical purposes, to be absolutely horizontal, and the preglacial sea surface to have been strictly parallel to the modern one. This remarkable coincidence between the present and preglacial sea levels over this immense area, the difference amounting nowhere to more than 10 or 12 feet, is a very striking and significant fact. Referring to the Sewerby beach Mr. Lamplugh says: "When we consider the time-interval and the great cycle of events which have passed since the stones of this old beach were rolled up by the sea, it is sufficiently remarkable that there should be so little difference in the sea level that the waves to-day resume their ancient work, and rearrange the same pebbles into another beach under the same old cliff."

Plate XIII.



SKETCH MAP
of
EUROPE
showing the extent and trend
of the
MAXIMUM GLACIATION.

To face p 103]

Stanford's Geogl. Estabt., London.

London: Macmillan & Co., Ltd

CHAPTER VI

THE GLACIATION OF EUROPE

The Baltic Centre of distribution—Its position to the east of the Scandinavian mountains—Extent of the European Ice-sheet—The crossing of the North Sea—Characters of the older and newer drifts—Their relation to the loess, to Palaeolithic man, and to the Quaternary mammals—The Baltic moraine—Its parallelism to the Baltic coast and the types of landscape connected with it—The course of the moraine traced in detail—Description of its characters—The moraines of the Christiania Valley—The Ra-moraines—The Lake Wener moraines—The Vaberg moraine-series and their possible connexion with the Brückner Periods—The Salpausselkä—The glacial topography of Finland—The interglacial question—The Eemian deposits.

The Baltic Centre.

The immense ice-sheet which covered north-western Europe in Quaternary times had its main centre of distribution in the northern part of the Baltic basin. Hence it spread out in all directions, sending ice north into the Arctic Ocean, east and south on to the plains of Russia and Germany, and west over the shallow basin of the North Sea even to the shores of England. It overrode the lofty mountain ranges which form the axis of the Scandinavian Peninsula, and pushed out seawards, probably to the very margin of the Atlantic shelf. Its thickness we have little means of calculating, but it must certainly have reached enormous figures. Probably 10,000 feet would be no over-estimate.

The position of the centre of distribution over the Gulf of Bothnia was attained during the maximum and later stages of development. There can be little doubt, though we have no direct proof of it, that accumulation first began on the Scandinavian Mountains, and that the ice spread west and east from the water-shed, pouring down the fjords into the Atlantic, and spreading out on the more gently graded eastern slopes of the country. The Norwegian glaciers, on account of their steep gradient and comparative rapidity of movement, and the facility with which they must have got rid of surplus ice by the calving of great bergs into the Atlantic, effectually drained the western slopes for some time. Not so on the Swedish side, however. Every mile that the ice pushed forward on to the plains rendered further advance increasingly difficult. Only the accumulation of greater snow-fields behind made motion possible, and thus the eastern ice heaped itself up much more rapidly than the western. Finally, as the glaciers coalesced and spread out as an ice-sheet over the basin of the Baltic, the snow-fields on the eastern slopes rose till they towered above the mountain passes to the west, and began to pour their ice through these passes to join that already moving towards the open Atlantic. Throughout the higher reaches of the Swedish valleys there is spread abundant erratic material which has been transsported from east to west, from lower levels to higher, and even carried over the summits of the passes into the Norwegian fjords beyond.

A free outlet to the west for all ice accumulation above a certain level (determined by the height of the Scandinavian Mountains) being thus established, further displacement of the centre of accumulation and dispersion took place, and we cannot doubt that, owing to the relatively easy escape to the west, and the increasing difficulty of advancing an ever-widening frontier on the European plains, this displacement went on right up to the maximum of glaciation.

Glaciation of the European Plain.

During the maximum the ice spread east as far as the foot of the Timan Mountains in northern Russia. These mountains formed a more or less independent centre of dispersion, and with the Urals sent down glaciers over the plains of the Petschora. To the south the ice-sheet descended beyond the 50th parallel of latitude, overriding the Valdai Hills, and sending great tongues along the valleys of the Dnieper and Don. Between these ice-lobes lay an unglaciated area somewhat similar to the driftless area of Wisconsin, but the ice does not appear to have reunited to the south as in the American case.

All this immense glaciated area is buried in a thick mantle of drift which also extends west over the North German Plain. Here the ice reached the northern slopes of the Carpathians and Riesengebirge, and sent out a lobe in a south-easterly direction between the Erzgebirge and the Harz. It hugged the northern face of the latter mountains, and lodged erratic blocks on their slopes to a height of over 400 metres. It appears to have covered the greater part of the area now occupied by Holland, and certainly spread almost entirely over the basin of the North Sea so as to coalesce with, and largely influence the motion of, the more or less independent British ice-sheet.

Advance of the ice over the North Sea basin.

The conception of the occupation of the North Sea by land ice from Scandinavia presents little difficulty. The extreme shallowness and the level nature of its floor made it an easy conquest to the advancing glaciers, and there can be little doubt that the accumulation of snow on the broad surfaces of these as they coalesced and spread out over the plain formed a powerful auxiliary to the supply from behind. It has indeed been even suggested that an ice-sheet with its own centre or centres of accumulation and dispersion, and more or less independent of supplies from Scandinavia, may have grown up in the North Sea basin. But it is a simple conception, and more in accordance with observations in Germany and Russia, to suppose a simple radial outflow from the Baltic centre in all directions towards the peripheral zone of melting. There is no doubt, however, that once the ice-sheet occupied any district the snowfall on its surface became an important factor in aiding its growth, and it may well have been that, although the ice which occupied the North Sea and impinged on the coasts of Britain came in the main at first from the Scandinavian centre, it was at a later stage largely local in origin.

Crossing of the Scandinavian deep.

The Scandinavian deep has frequently been cited as an insuperable obstacle to the advance of the Scandinavian glaciers in a south-westerly direction. It is held that no ice-sheet could cross over a lane of water some 300 to 400 fathoms deep and 65 miles broad without being broken up into icebergs. A moment's consideration will show, however, that even if such breaking up into icebergs took place, these must in time, as the thickness of the ice-sheet increased, have attained such magnitude and floated so deep in the water that their escape to the open Atlantic would become impossible except sideways along the channel itself. Under such conditions it is clear that blocking of the channel was inevitable, and the floating ice may thus easily have been overridden by that coming from behind, and pressed down into the depths. Besides, it is not at all clear that the ice-sheet could not bridge the channel by floating as a whole, as we know that the Great Ross Barrier in the Antarctic does at the present day (see p. 23), and, of course, if this be admitted all difficulty vanishes at once.

However, with regard to the advance of the great European ice-sheet we can know little except by inference. Its records have become obscured by subsequent erosion and deposition, and must for ever remain for us a sealed book. The story of its retreat, however, lies open before us, and is one of absorbing interest. We can trace its successive stages with remarkable clearness, and our ever-advancing knowledge is enabling us to interpret the varying conditions attendant on each stage.

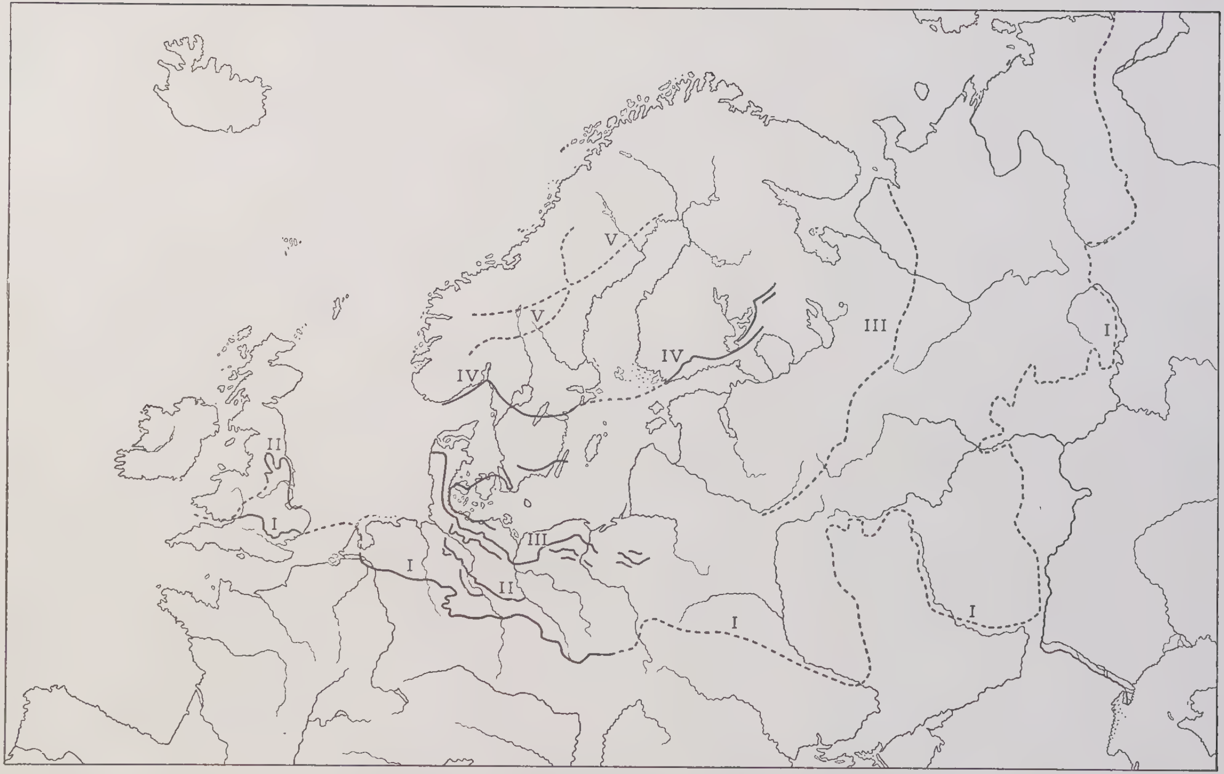
The retreat.

Contrast between the older and newer drifts.

The outer margin of the European drift is everywhere characterised by its advanced state of erosion. Valleys have been excavated through the boulder-clay, and a certain maturity of drainage attained. This is in striking contrast with the more northerly portions of the drift-sheet which exhibit marked immaturity or even absence of drainage, and abound in innumerable undrained lakes and completely enclosed basins. It is obvious that the marginal belt of the glaciated area was abandoned by the ice-sheet long before the more central and northern areas, and was undergoing subaerial erosion while the latter was still covered by ice. If it were not for the fact that we have no means of gauging the severity of this denudation, we might feel inclined to say that the period during which it was in progress was much longer than that which has elapsed since the complete disappearance of the ice. Such a conclusion would, however, be very unsafe, since in addition to the rigours of the glacial climate, the inevitable scantiness of vegetation on the newly exposed drift would facilitate erosion. What we do know is that on the Continent, as in England, the southern margins of the drift were exposed to severe denudation, the evidences of which are entirely wanting in the northern portions.

There is, however, another noteworthy distinguishing character of the southern drift. This is its uniformity of type, and relative absence of the well-known topographic forms of esker, kame, drumlin, and moraine so markedly developed farther north. This is especially noteworthy as regards the absence of moraine features. In fact the great ice-sheet of Europe had practically no terminal moraine at its maximum extension. Its ground-moraine dies out gradually in a southerly direction, and not only exhibits no distinct marginal phase, but even its margin is extremely hard to trace. The importance of this fact cannot be over-estimated, for it must be clear to every one that there is an essential difference between an ice-sheet which deposits a terminal moraine and one which leaves no such record around its margin.

The limits of the inner or newer drift with which the outer or older belt is in such marked contrast are shown in the accompanying map of Europe. It is noteworthy that this drift-sheet, unlike the older drift, has a distinct terminal moraine which, however, is not



Emery Walker sc.

FIG. 41.—Outline map of Northern Europe showing the main stages of retreat of the ice-margin.

I. Maximum. II. The Young End-moraine (margin of the loess-free drift). III. The Baltic End-moraine. IV. The Ra-moraines, Wetter moraines, and the Salpausselkä. V. The last ice-remnant.

nearly so pronounced as those formed during later stages of the retreat. It exhibits, moreover, a certain newness in its topography, and a relief unshared by the drift to the south. But the evidence which above all demonstrates the distinctness of these two sheets in point of age is the relation, pointed out by Penck,[1] which they bear to that remarkable deposit the loess and to Palaeolithic man. The older sheet is covered with loess, the newer is almost entirely free from it. Within the area of the older drift are numerous localities where the remains of Palaeolithic man and the animals associated with him abound, on the newer drift-sheet no trace of either has ever been found.

Relation to the loess and to Palaeolithic man.

It is the clearest evidence of the contemporaneity of man with the glacial period that his remains are absent over the greater part of the glaciated district, and abound outside it and along its margins. His principal haunts lay, it is true, some distance from the margin of the ice-sheet in southern Europe, especially in France and Austria. But his remains occur also in Germany close up to the margin of the drift, and in many cases resting upon it. He certainly survived the maximum of glaciation and migrated on to the older drift-sheet left free by its retreat, but it is just as certain that he left the country for good before further retreat laid bare the newer drift. This sudden southward retreat is one of the most extraordinary and inexplicable problems connected with the Pleistocene glaciation.

Palaeolithic stations later than the older drift.

The most famous German localities occupied by Palaeolithic man after the withdrawal of the ice are Thiede and Westeregeln near Brunswick, Weimar, Gera, Schussenried, and Thayngen. The calc-tufa at Weimar, which contains worked flints, charcoal, and charred bones, along with an uncommonly rich Pleistocene fauna, lies on Quaternary gravel containing northern erratics which could only have reached their present position as a consequence of the glaciation. The Lindenthal

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[1] Albrecht Penck, "Mensch und Eiszeit," *Archiv für Anthropologie*, Bd. xv., 1884.

Cave is, as Liebe proved, distinctly younger than the neighbouring northern diluvium, that is to say, than the moraine of the Scandinavian glaciation. The same can be maintained with regard to Thiede. Schussenried and Thayngen in south Germany bear the same relation to the outer moraine of the Alpine glaciation as the other localities do to the northern drift. The beds of Schussenried lie immediately on moraine, and the Kessler Hole near Thayngen lies in a valley which is younger than the moraine of the district.

Inter-glacial character of the Weimar fauna.

A comparison of the faunas associated with the Palaeolithic remains of Schussenried and Weimar raises another point of interest to which Penck has drawn attention. The fauna of Schussenried is distinctly arctic, and the mosses associated with it are northern forms. It is clear that man lived here under glacial conditions. The case of Weimar was quite different. Reindeer and lemming are both absent. The roe, the stag, the wolf, beaver, wild-boar, and aurochs were then, as in post-glacial times, the contemporaries of man, and it can only be presumed that the latter lived under relatively temperate climatic conditions, a conclusion which is supported by Kriechbaumer's investigation of the molluscan fauna. It is clear, however, that we are not really dealing with a post-glacial deposit, for remains of the cave lion, cave hyaena, *Elephas antiquus*, and *Rhinoceros merckii*, as well as some extinct molluscs, are associated with the still surviving animals, and characterise the whole as distinctly Quaternary. This, moreover, is stratigraphically proved by the loess covering.

The conclusion obviously to be drawn from this is, that Palaeolithic man occupied Weimar during a temperate period intervening between the maximum of glaciation and the cold period represented by the newer drift-sheet. We shall prove in another chapter that the loess was deposited during, or at the end of, this temperate period. That man persisted in Germany into the later stage of glaciation is shown by his occurrence at Schussenried in association with a glacial fauna actually on the older moraine of the Alps.

The extent to which the ice-sheet withdrew north during this temperate period is and must long remain a matter of opinion. I am myself inclined to believe that the retreat was inconsiderable, but I can urge little reason for the belief except an absence of evidence to the contrary, and it must be admitted that such evidence would not often be preserved.

The Baltic end-moraine.

It is not till some distance in from the ill-defined margin of the newer drift that belts of terminal moraines begin to form a prominent feature of the landscape. The best preserved and most clearly marked of these is the great Baltic end-moraine, which has been traced as an almost uninterrupted belt for a distance of more than 1000 km. from the north of Denmark to West Prussia, and has been proved in a few places in East Prussia, and even farther east, while there is little doubt that it will be ultimately traceable through Russia to the northern ocean. It exhibits throughout a great part of its course a remarkable parallelism with the southern boundary of the Baltic Sea. Schröder was the first to point out this parallelism, which indeed is so pronounced that a genetic connexion must certainly exist between the two.

and its parallelism to the Baltic coast.

Its structure and form.

In its most typical form this end-moraine belt is represented by a series of wall and ridge shaped heaps of blocks, boulders, and smaller debris. These form curves and loops with their convexities to the outside, *i.e.* towards the district which was ice-free at the period of their formation. Several parallel or sub-parallel ridges often occur one within the other, marking different stages of the retreat. Outside the moraine belt is typical fluvio-glacial foreland produced by the outwash of sand and gravel from the ice front, and forming the well-known heath-landscape. On the inside, on the contrary, is the so-called ground-moraine landscape, with its numerous little ponds and depressions or elongated lake troughs, constituting the Baltic lake

The types of landscape on either side of it.

district which forms so remarkable a feature on the map of Europe.

The course of the moraine in Jutland is irreconcilable with De Geer's Baltic Glacier.

The end-moraine, which takes a northerly course along the centre of the peninsula of Jutland, turns sharply to the west at Dollerup, in the north of Denmark, and reaches the North Sea south of Lemwig. This sharp bend to the west has a particular interest as it is one of the principal arguments against De Geer's famous hypothesis of the Baltic Glacier. De Geer supposed that the end-moraine was formed by an ice-tongue which was fed entirely from the neighbourhood of the Gulf of Bothnia, and received no contributions from southern Sweden or Norway. In fact he imagined the south of Sweden to have been ice-free at this period, and conceived of the northern margin of his glacier as being roughly coincident with its coast. It is clear, however, from the westward bending of the Danish end-moraine, that there must have been a powerful ice-movement towards the south off the mountains of Norway at the period of its formation, and since the course of the end-moraine shows a remarkable parallelism to the shores of the Christiania fjord and the Cattegat, it seems probable that the ice which formed it came in part over southern Sweden as well. Holst has brought forward much additional evidence in support of this conclusion.[1]

The course of the moraine traced through Schleswig-Holstein

The best known part of the great Baltic moraine is that which traverses Schleswig-Holstein. Its true nature was first recognised in this district by Johnstrup, but it is to the more recent work of Gotsche[2] that we largely owe our present detailed knowledge of it. It is composed of a series of bows or loops whose radii represent approximately the direction of ice-motion at the margin at the time of its formation. It is very varied in its development, being totally absent in some places, and represented only by a boulder-belt in others, but it generally forms distinct hillocks or wall-like ridges. It is more or less independent of contours, ranging in altitude from 10 m. to 150 m. over the sea. In front of the moraine, that is to say to the west of it, stretch as a rule plains composed of sand, with but few stones, deposited by the outwash waters from the melting ice. In this sandy foreland there occur at a distance of from 10 to 40 km. from the end-moraine, isolated "steinpackungen," and districts with abundant stones, which in all probability are the remnants of an outer moraine feature such as that developed a little farther east in Mecklenburg.

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[1] Nils Olaf Holst, "Har det funnits mera än Istid i Sverige," *Sveriges Geologiska Undersökning*, Ser. C. No. 151 (1895).

[2] G. Gotsche, "Die Endmoränen und das marine Diluvium Schleswig-Holsteins," *Mitteil. d. geogr. Ges. in Hamburg*, Bd. xiii.

into Mecklenburg, where remains of an older, outer moraine are easily distinguishable.

The Schleswig end-moraine follows throughout the greater part of its course the general northerly direction of the peninsula of Jutland, but at Rendsburg it bends away in a south-easterly direction parallel to the general coast-line of the Baltic, and continues in this direction into Mecklenburg. Here it has been carefully studied by Geinitz, who distinguishes two principal features: the main northern moraine and the main southern moraine, as well as a couple of minor remnants respectively north and south of these. The main northern moraine is a direct continuation of the Schleswig-Holstein end-moraine, and except where it is interrupted by the Gulf of Lubeck, has been traced without a break throughout Mecklenburg. It resembles in all its features that of Schleswig-Holstein.

The main southern moraine lies on the southern boundary of the lake district of Mecklenburg, at a distance of about 30 km. south of the northern one, although it is not nearly so well preserved as the latter. Its course has been traced by Geinitz for a distance of 210 km. Its intermittent character he explains through subsequent destruction by washing and burial in sand deposits. It traverses Mecklenburg in a series of loops, which show a certain rude parallelism with those of the northern moraine, and have like them their convexities towards the south. Both moraines pay little heed to contours, and pass over some of the highest points of the district. The lake district of Mecklenburg occurs between them, the depressions of some of the biggest lakes being bounded both to north and south by the moraines. The landscape forms passed in turn in a traverse from north to south across these moraines are as follows:

(*a*) Ground-moraine plain.
(*b*) End-moraine (younger).
(*c*) Outwash sand or clay.
(*a′*) Ground-moraine.
(*b′*) End-moraine (older).
(*c′*) Outwash sand.

There is here, therefore, clearly marked evidence of a retreat by stages, the sand plains of the inner or northern stage not reaching south to the older moraine, but dying out so as to let the ground-moraine appear again at the surface before the southern moraine is reached.

In the provinces of Uckermark and Neumark, in the basin of the Oder, a different order of things sets in. We have here a parallel series of three moraines, but none of these appear to correspond to the outer moraine of Mecklenburg. Indeed the most southerly of the Uckermark-Neumark moraines is conterminous with the inner or main northern moraine of Mecklenburg, and no prolongation of the main southern moraine has as yet been detected in these provinces. The manner in which the main Baltic moraine sweeps in a great loop across the basin of the Oder, and changes its direction from south-east to north-east, is one of the most striking examples of the tendency shown by this feature to preserve a certain parallelism to the general trend of the coastline of the Baltic. This great arc of moraine was laid down by a tongue of ice which occupied the central depression of the Gulf of Oder, and has been named by Keilhack the Oder Glacier. That its existence was more or less connected with that depression either as cause or effect there can be little doubt.

The moraines of the Oder Glacier in Uckermark and Neumark.

Of the inner moraines of Uckermark, the most remarkable is the Fürstenwerder-Gerswalde moraine, which lies about 10 km. north-east of the main moraine with which it preserves a strict parallelism. It is continued for a short distance across the Oder into Neumark.

Still farther south lies a third moraine belonging to a remarkable type which occurs here and there in all the moraine belts. Features of this type have been termed by Schröder "Stau-moräne," and they are referred to by him as "Durchragungszüge" on account of the manner in which the contorted masses of sand, gravel, and ground-moraine which compose these features project through the cloak of upper moraine (or englacial material) which laps up on their flanks. They have undoubtedly been formed by ice pressure acting from one side and pushing the gravels and boulder-clay up into ridges. That they are best regarded as a special type of end-moraine, marking a halt in the retreat of the ice-margin, is shown by their similarity of form and general parallelism to these features. In Neumark there are three moraine features of a similar type occupying a similar position with regard to the main end-moraine, and no doubt approximately equivalent in age to that of Uckermark.

The topographic belts of Pomerania.

The end-moraine of the Baltic "Höhenrücken" in Pomerania has become known through the investigations of Keilhack.[1] He showed that just as in Schleswig-Holstein and elsewhere along the southern margin of the Baltic, the country exhibits belts of different types running parallel to the coast. Following on the coastal dunes, and the lakes and moors behind them, is a smooth belt of boulder-clay, lying some 10 to 80 m. above the sea, and about 40 km. broad. The third belt is a hilly country deeply trenched by erosion valleys and the broad old diluvial valleys, and composed in great part of the beds of the "lower diluvium." Advancing south and rising rapidly one reaches the actual Höhenrücken, which is mainly composed of upper boulder-clay, possesses a height of 120-300 m. over the sea, and is characterised by an abundance of closed depressions filled with water or peat. On the southern margin of this belt, and separating it from the heath-forming sand-plains, is a narrow strip of end-moraine agreeing in its structure, looped form and independence of contours with that of the other districts. The succeeding heath landscape is in sharp contrast to the moraine landscape. Close to the boundary of the latter it is composed of coarse-grained materials, and is somewhat uneven in surface, but farther south it is merely undulating, and passes ultimately into a level sand plain.

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[1] Keilhack, "Die baltische Endmoräne in der Neumark und im südlichen Hinterpommern," *Jahrb. d. preuss. geol. Landesanstalt*, 1894, p. 227; "Der baltische Höhenrücken in Hinterpommern und West-Preussen," *ib.*, 1889, pp. 149-214.

The continuation of the moraines into Prussia.

At Dramburg in Pomerania the Baltic end-moraine splits into two, which diverge gradually towards the east. The southern branch is rather complex, and embraces many parallel features, but it can be traced along with the northern branch as far as the Vistula.[1] A short distance beyond this river both appear to break off suddenly, but it is probable that subsequent mapping will determine their further courses through East Prussia and Russia.

The Southern or Posen moraine.

Far to the south, in southern Neumark, and in the province of Posen, Berendt and Keilhack[2] have proved the existence of a marked end-moraine feature stretching south-east from Zielenzig to the Russian border between the rivers Warta and Oder. It is not so well marked or so well preserved as the Baltic end-moraine, but nevertheless forms a connected feature. It may possibly be the equivalent of the southern or older moraine of Mecklenburg.

Probable continuation of the Baltic moraine in Russia.

End-moraines in every way similar to those of the great belts of North Germany, and like them associated on their inner side with drumlin landscape and on their outer with sand-plains, have been described by Anna Missuna [1] as occurring in the Governments of Minsk, Wilna, and Witebsk in Russia, and Glinka [2] has given an account of similar phenomena in the Government of Pskow, where the moraines occur at the outer boundary of the lake district. These moraines are very probably a continuation of the Baltic End-moraine, and there is little doubt that this will ultimately be traced throughout Russia to the Arctic Sea.

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[1] O. Maas, "Über Endmoränen in Westpreussen und angrenz. Gebieten," *Jahrb. d. preuss. geol. Landesanst.*, 1900, p. 93.

[2] G. Berendt, "Die beidenseitige Fortsetzung des südlichen baltischen Endmoräne," *ib.*, 1888, pp. 110-122; "Vier weitere Teilstücke der grossen südbaltischen Endmoräne," *ib.*, 1894, pp. 222-234. G. Berendt und K. Keilhack, "Endmoränen in der Provinz Posen," *ib.*, 1894, pp. 235-251.

Summarised description.

We have now traced, as far as it is known, the course of the great Baltic End-moraine. We have seen that in the west of Germany it consists of only two ridges, but that when followed east it becomes much more complex and splits up into diverging branches. The main or northern ridge is almost continuous from the west coast of Denmark to the Russian frontier, and preserves throughout a striking parallelism with the coasts of the Skager Rack, Cattegat, and Baltic. The southern or older ridge runs parallel to the northern in Schleswig-Holstein and Mecklenburg, but near the junction of the Rivers Warta and Oder its probable equivalent diverges considerably to the south. The wider spacing and greater number of the moraines in the east shows undoubtedly that the retreat was at this stage more rapid and continuous here than in the west. The main or younger moraine follows generally the watershed of the Baltic Basin, and separates two belts of country of entirely different aspect. On the one hand is the pronounced drumlin topography of the ground-moraine, on the other, the level or gently undulating sand-plains of the outwash. Where a second moraine feature occurs, the sequence of ground-moraine, end-moraine and sand-plain is repeated with it. The Baltic Lake District lies entirely within the end-moraines, the lakes being a natural accompaniment of the pronounced topography produced during the later stages of the retreat.

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[1] "Über die Endmoränen von Weissrussland und Lithauen," *Z. deutsch. geol. Ges.*, 1902, p. 284.

[2] Glinka, "Einige Beobachtungen im Gebiete der posttertiären Ablagerungen des nordwestlichen Russland," *Annuaire géol. Russie*, iv., 1901, p. 115.

Petrographically there is little or no distinction between the ground-moraine within and without the moraine-belt. This is held, and with some reason, to show that the moraine merely indicates a pause in the retreat, and that little or no readvance preceded its deposition. It certainly seems to indicate that the moraine does not mark the maximum extension of an independent glaciation, as has been maintained by many eminent glacialists.[1]

Further stages of retreat.

As relics of more advanced stages of retreat we have several rather doubtful features in Southern Sweden, and then we come to the great Ra-moraines of the Christiania Fjord. The ras are two in number, and, like the members of the Baltic end-moraine, parallel to one another. The outer ra, which has been traced farthest, has a V-shaped course across the Christiania Valley in rough conformity with the shape of the coast. It skirts the coast of Southern Norway as far as the Naze, lying partly on land and partly beneath the sea. On the other side of the fjord, it is less strictly parallel to the coast, and runs inland towards the southern end of Lake Wener. It is succeeded in the upper reaches of the Christiania Valley by five other moraine steps, the whole forming the following series :—

1. The outer ra.
2. The inner ra.
3. The moraine between the inner ra and the "epiglacial" moraine.
4. The "epiglacial" moraine, south of the ends of the large lakes of Central Norway.
5. The moraine between the epiglacial and uppermost moraines.
6. The uppermost moraines.

This series of moraines has a quite exceptional interest on account of Brögger's remarkable investigations[1] into the sea-level at the time of their formation. He has succeeded in establishing, as we will fully show in a subsequent chapter, that the sea, which appears to have stood at a low level during the Ice Age, attained for the first time its present height on the land when the ice-margin stood at the outer ra. From this stage on it rose, as the ice retreated, until it reached a maximum height at the epiglacial stage of the retreat. Thus the moraines of the Christiania Valley from the outer ra to the epiglacial moraine were deposited beneath the waters of the sea.

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[1] An admirably complete account of the glacial deposits of the North German plain is given by Felix Wahnschaffe in his work, *Die Oberflächengestaltung des norddeutschen Flachlandes*. Stuttgart, 1909.

Although the sea stood highest on the land during the epiglacial stage, yet, on account of the altitude at which these moraines lie, there was little depth of water at the ice-margin during their formation; and as there was no subsequent deepening, but on the contrary a marked shallowing from this on, the sea did not occupy the country exposed by the farther retreat of the ice from the epiglacial moraines. The moraines of the two last stages were, therefore, not formed beneath sea-level.

The great moraines of Sweden.

Up to the present the exact equivalent in Sweden of the ra moraines of Christiania has not been determined. The great moraine ridges which traverse the southern part of the basin of Lake Wener were very probably formed at the same time, but there is a considerable gap between them and the most easterly point to which the ra can be traced in which no moraines are known. In the basin of Lake Wener there are three principal features, and it is the most southerly of these which is most likely equivalent to the outer ra of Christiania. The remarkable moraines of the Vaberg district described by Hedström[2] are probably equivalent in age to the more northerly of the Lake Wener moraines, and are therefore to be regarded as a little younger than the outer ra.

The morainic series of Vaberg.

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[1] W. C. Brögger, "Om de senglaciale og postglaciale nivåforändringar i Kristianiafeltet," *Norges Geologiske Undersögelse,* No. 31 (1901).

[2] Herman Hedström, "Om ändmoräner och strandlinier i trakten af Vaberget." *Geol. Fören. Förhandl.* Bd. xxiii. p. 163 (1901).

The district of Vaberg is near Karlsborg, on the Gotha Canal connecting Lakes Wener and Wetter. Here Hedström has distinguished three series of moraine ridges succeeding one another from south to north in the following order :—

(1) The Mölltorp Series.
(2) The Vaberg Series.
(3) The Forsvik Series.

There is an interval of 1 km. of moraineless country between the Mölltorp and Vaberg Series, and 2 km. between the Vaberg and Forsvik Series. The Forsvik Series contains some 16 parallel moraine ridges, of which the 8 most southerly, which are the best exposed and most easily traceable, lie at distances of 100 to 225 m. from one another, with an average interval of 150 m. The ridges are all of small dimensions, having a breadth of about 15 m. at the base and a height varying from 1 to 3 m. The largest is the third from the south, which in places is 4 m. high. In spite, however, of their diminutive size, they are traceable with wonderful continuity across the country, receding north a little on the heights and pushing south again in the valleys. All are composed of typical moraine stuff quite unbedded.

The Vaberg Series consists of 17 parallel ridges of height and dimensions similar to those of the Forsvik Series, and occurring at similar intervals. The details of the Mölltorp series have not yet been investigated.

The periodicity indicated by them.

The circumstance that the end-moraines occur in series with longer intervals is remarkably significant. We have thus to deal with a double periodicity, the periodicity of the series, and the periodicity of the small end-moraines composing the series. If the latter be regarded as yearly, then some longer period must be assigned to the intervals between the series. If we look to modern records for a suitable climatic oscillation, we find it in the Brückner Periods.[1] These are set forth for the last two centuries in the following table :—

Possible connection with the Brückner Periods.

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[1] Brückner, *Klimaschwankungen*, p. 232.

1691–1715	Cold damp	25 years
1716–1730	Warm dry	15 ,,
1731–1745	Cold damp	15 ,,
1746–1755	Warm dry	10 ,,
1756–1770	Cold damp	15 ,,
1771–1785	Warm dry	15 ,,
1786–1790	Cold damp	5 ,,
1791–1800	Warm dry	10 ,,
1801–1820	Cold damp	20 years
1821–1835	Warm dry	15 ,,
1836–1845	Cold damp	10 ,,
1846–1870	Warm dry	25 ,,
1871–1885	Cold damp	15 ,,
1886–1895	Warm dry	10 ,,
1896–1909	Cold damp	14 ,,

The average for the cold-damp periods is a little under 15 years, and for the warm-dry periods 14¼ years. We have, however, a possible range of 5 to 25 years for the former, and of 10 to 25 years for the latter. It is clear that Hedström's moraine periods of 16 and 17 years' duration are quite conceivably referable to these climatic oscillations. In view of the fact that the earlier stage of the retreat on the German plain took place during the dry steppe climate of the loess period, and was unaccompanied by moraine formation, we must ascribe the formation of the moraine series to the cold-damp periods of Brückner, and suppose the moraineless intervals to have been laid bare during the intervening dry-warm periods. This is quite consistent with the *a priori* conception of the action of the glaciers which, in order to form moraines, must have active motion right up to their margins, such as would result from greater accumulation on the snow-fields above, during the more copious precipitation of the cold-wet periods. Greater activity of motion must in general result in advance of the ice-margin, and each Brückner period would in that case result in the production of a single large moraine. But it is conceivable that a state of balance might be reached when the additional supply from behind just failed to make good the ever-present marginal waste. In that case we would get moraine series of the type described by Hedström, in which the more pronounced though shorter yearly oscillation is alone manifest in converting the retreat of the margin into an actual advance.

The Salpausselkä.

The two huge parallel sand ridges, which in a great bow surround the lake district of Finland, are end-moraines of the ice-sheet. The more southerly, which follows the watershed of the country, is known under the name of Salpausselkä. A glance at the map (p. 108) is sufficient to show that these moraines must belong to approximately the same age of retreat as the ras of Christiania, and the great moraines and moraine-series of the basins of Lakes Wener and Wetter. Like them, they appear to have been deposited beneath sea-level, and Sederholm[1] is of opinion that their sandy and gravelly stratified nature is largely due to this. Several minor parallel features, which have been detected to the north, are also probably to be regarded as moraines.

Topography of Finland.

There is a remarkable contrast in the topography of the districts lying south and north of the Salpausselkä, and in general between the coastal tract and the interior of Finland. In the coastal district bedded clay deposits are common, and all the drifts exhibit to a greater or less degree traces of the action of the sea, so that a certain softening of the contours results. Between the two ridges these stratified deposits are still common. North of the second ridge the surface is almost entirely composed of unstratified till or boulder-clay, and the marine clays and sands are extremely limited in their development. The till forms elongated ridges or drumlins 10 to 15 or even 30 m. high, with their longer axes parallel to the direction of ice-motion. These drumlins are the determining feature of the peculiarities in the configuration of the surface of the country, the direction of the valleys and of the smaller lakes and inlets being dependent on them. In fact, the distribution and form of the lakes gives a large scale map of Finland quite a striped appearance.

The most striking character of the interior of Finland is certainly its richness in lakes; in which respect it is surpassed by no other region in the world. These lakes are produced by the unevenness of the ridged surface of the ground-moraine, and only a few of them owe their origin to the damming effect of the end-moraine. Nevertheless, the Salpausselkä, broadly speaking, marks the southern limit of the lake district. The production of lakes to the north of the moraine, and not to the south of it, depends on the entirely different activities of the ice when it laid bare these two districts.

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[1] J. J. Sederholm, "Om istidens bildningar i det inre af Finland," *Fennia*, vol. i. No. 7, 1889.

The ice-dammed lakes of Scandinavia.

On account of the eccentric position of the Scandinavian ice-sheet, which lay not on the watershed but considerably east of it, a peculiar condition of affairs arose during the later stages of retreat. The lower reaches of the eastward draining valleys remained blocked with ice long after their heads had become free. A number of lakes were thus instituted which drained either one into the other or directly across the lower passes in the watershed. In many cases distinct shore-line terraces can be seen contouring the sides of the valleys at the level of the pass at its head. These extend some distance east, and are then cut off suddenly at the point where the former ice barrier stood.

The stages of retreat reviewed.

We may now, before passing on to other matters, briefly review the various stages of retreat which we have in turn considered. We have seen that in the early stages, when the older drift of the European plain was laid bare, few or no end-moraines were formed, and a rather featureless sheet of drift was left behind. On this, while the ice still occupied the country immediately to the north, the loess was deposited with accompanying remains of palæolithic man and the quaternary mammals which he hunted. At a distinctly later stage, as is shown by the contrast in denudation between the older and newer drift, the retreat was continued. No loess, however, was formed on the surface of the drift thus laid bare, and by this time man and the quaternary mammals had disappeared from the country. A distinct moraine, the Young End-moraine, marks the limit of newer drift, but it was not till a still later stage that the retreat was characterised by marked moraine formation. Most of the moraines seem to be accompanied by a drumlin area on the north, and an area of outwash on the south. Two principal moraine belts have been distinguished, namely, that of the Great Baltic End-moraine, and that of the Ra-moraines and the Salpausselkä. The former belt appears to have been formed on land and the latter beneath the sea. Finally, at the very last stage lakes were held in between the watershed of Scandinavia and the decaying ice-shed to the east of it.

The interglacial question.

An account of the glaciation of Northern Europe such as has been given above would be very incomplete without some discussion of the problem of interglacial periods. It is necessary to consider carefully if there is reliable evidence tending to show that any two of the phases described above were separated by a period of marked retreat, during which the ice-margin lay considerably farther north. The elaborate systems of the older interglacialists may all be set aside as unproved. The class of evidence on which they were founded will not stand critical examination. For instance, the superposition of different sheets of till may at the most mean change in the direction of ice-motion. The occurrence of interbedded gravels may merely mean local oscillation, or may be due to the natural formation of subglacial gravels between the ground-moraine and englacial moraine. Fossiliferous beds between sheets of boulder-clay, unless they are clearly proved to be still in the position in which they were deposited, may have been caught up from the preglacial floor. The greater weathering of the older drift-sheets may have been effected while the newer sheets were being deposited. It will thus be seen that it is a distinctly difficult thing to prove an interglacial period. We must, however, as Mr. Lamplugh has long maintained,[1] get back to solid ground in this matter before it is possible to make any real advance. There have been altogether too many speculations and too many loose correlations from place to place in dealing with this problem. We are bound to take our stand on the comparatively simple monoglacial hypothesis until we can prove at least one interglacial period. It will then be time enough to proceed to consider further possibilities.

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[1] G. W. Lamplugh, "British Drifts and the Interglacial Problem," Presidential Address to the Geological Section of the British Association, York, 1906.

Now it would be quite outside the scope of the present volume to adequately discuss all the known deposits of possible interglacial age; and as the verdict would only be a negative one, the attempt will not be made. It will be much more to the point to give some account of a recent investigation which supplies satisfactory evidence of an oscillation of very considerable magnitude. In the year 1908 Victor Madsen, Nordmann, and Hartz published an account[1] of a systematic study of the Cyprina Clays of Denmark, North Germany and Holland. These clays have been much studied in the past, and a considerable literature has grown up around them. They were referred by Geikie and other interglacialists to one of the interglacial periods, but as they are largely transported masses embedded in the boulder-clay it was very justly held by the monoglacialists that they might easily be of preglacial age. This latter idea has, however, proved to be untenable. The transported masses when studied in detail exhibit a regular and constant succession of beds which shows an upward passage from freshwater through brackish into marine deposits, and is so well characterised by its peculiar assemblages of fossils that it is readily identifiable wherever it occurs. It has been called by the authors the Eem-zone or Eemian. Now the localities where the Eemian deposits occur as displaced masses incorporated with the ground-moraine all lie in the east of Denmark and the north of Germany. To the west and south of this area they are undisturbed and in their original position. Here also they can be seen to rest on boulder-clay and fluvio-glacial gravels, so that it is obvious they are not preglacial. This

The interglacial Cyprina clays.

The Eemian deposits

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[1] Victor Madsen, V. Nordmann, and N. Hartz, "Eem-Zonerne. Studier over Cyprinaleret og andre Eem-Aflejringer i Danmark, Nord-Tyskland og Holland," *Danmarks geologiske Undersögelse,* II. Række, Nr. 17, 1908.

relation is exhibited in Fig. 42. From this figure also it is clear that the line separating the disturbed and undisturbed Eemian deposits is neither the main Baltic Moraine nor the outermost Young End-moraine, but some intermediate line of less definiteness. Not that any actual displaced masses of the Eemian beds showing the actual succession have been found outside the Baltic Moraine, but the characteristic Eemian shells have been found incorporated with the ground-moraine outside this line; and the occurrence of these shells is regarded by the authors as sufficient evidence of the incorporation of Eemian deposits in the moraine.

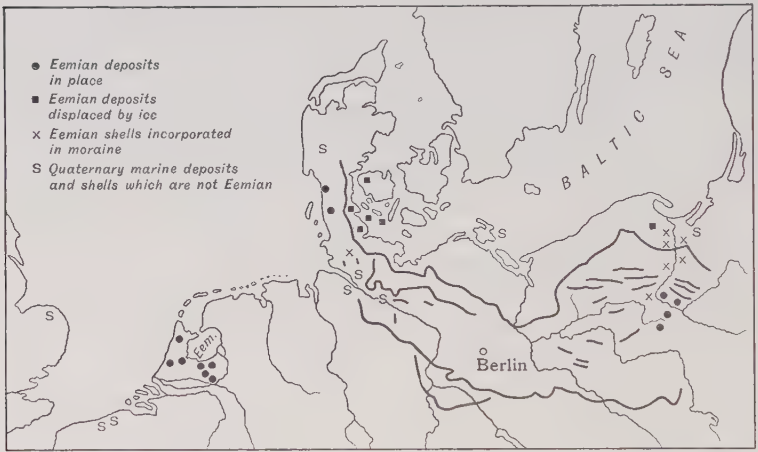
● Eemian deposits in place
■ Eemian deposits displaced by ice
× Eemian shells incorporated in moraine
S Quaternary marine deposits and shells which are not Eemian
BALTIC SEA
Berlin
Eem.
S
Emery Walker sc.

FIG. 42.—Map of the Eemian deposits of north-west Europe. The localities after Madsen, Nordmann, and Hartz, the main feature of the Baltic End-moraine and its outer wreaths after Wahnschaffe, the outermost Young End-moraine (margin of the loess-free drift) after Werth.

Extent of recession indicated.

Now this state of things shows clearly that the Eemian fresh-water estuarine and marine beds were laid down during a period of recession of the ice followed by readvance. The width of the belt in which the transported masses are found in the boulder-clay of the Baltic Ice Sheet is not very great, being at most about 50 miles. The nature of the marine fauna seems, however, to indicate a considerably greater retreat than this, being characterised by a small but well-marked group of southern species. Such Arctic species as occur are of wide distribution, and present themselves in forms such as the species assume towards their extreme southerly limits. The following are the most characteristic forms :—

Southern Species.	*Tapes aureus*, var. *eemiensis*.	Appears to be extinct.
	Lucina divaricata *Gastrana fragilis*	Northern limit in the southern part of the North Sea.
	Cardium tuberculatum *Cardium papillosum* *Haminea navicula*	Northern limit in the English Channel.
	Mytilus minimus *Syndesmya ovata*	Northern limit on the west coast of France.
	Mytilus lineatus.	Now confined to the Mediterranean.
Northern Species.	*Mya truncata* *Zirphæa crispata*	Southern limit the mouth of the Loire.
	Cyprina islandica.	Southern limit Archachon (Gironde).

This assemblage of fossils indicates very clearly that the present equivalent of the Eemian sea of Denmark is to be looked for in or near the English Channel. Some of the species are even more southern than this, but the presence of the last three cited forbids the pushing of the comparison farther south. The facts are, however, sufficiently striking. The existence of such forms is practically impossible close up to the ice margin. The extent of the recession must therefore have been considerably greater than the 50 miles quoted above. There is even a high probability of complete disappearance of the ice. Proof of an oscillation of interglacial magnitude is hardly likely to be pushed much further than this.

CHAPTER VII

THE GLACIATION OF THE ALPS

Contrast between the younger and older moraine of the Alps—The fourfold repetition of the foreland glaciation proved by the outwash gravels—The fluvio-glacial origin of the gravels—The four glaciations—Relation of the gravels to the loess—The moraines of the different glaciations—The completeness of the interglacial retreat proved by the intermorainic plant beds—The Riss-Würm Interglacial Period—The Höttinger Breccia—The "Schieferkohlen" of Dürnten, Wetzikon and Uznach—The plant-bearing clays of Re—The interglacial beds of Pianico—The calcareous tufas of Flurlingen and Entraigues—The interglacial clay of Calprino—Older interglacial periods—The quaternary fauna of the Alps in its relation to the glacial and interglacial periods—Paleolithic man—Wildkirchli—Physiographical conditions of the Würm Ice Age—Determination of the Würm snow-line—Its relation to the present precipitation and to the snow-line of the present day—The parallelism of the two snow-lines disproves the precipitation theory of the Ice Age—Extent of the Würm Glaciation and position of the ice-shed—Fauna of the Würm Ice Age—Flora of the Würm Ice Age and height of the tree-boundary—The tundras of the north and the woodland of the south—The Riss Ice Age and its snow-line—Remarkable deduction regarding the absence of the Adriatic—Mindel and Günz Ice Ages—Interglacial flora of the Alps—Duration of the ice-ages and interglacial periods—The retreat-stages Bühl-, Geschnitz- and Daun-stadia—Relation to the Magdalénien, Neolithic and Bronze Ages.

The importance of the Alps in unravelling the tangled chronology of the Ice Age has fortunately been long recognised. Since the time of Venetz, Charpentier and Agassiz, the study of the former development of its glaciers has attracted many eminent men, among whom Simony, Morlot, Heer, Brückner, Ramsay, Partsch, Du Pasquier, Depéret, and Heim occupy prominent places.

To none, however, do we owe so much as to Albrecht Penck, who has devoted a great part of his life to this work. In the magnificent memoir, *Die Alpen im Eiszeitalter*, recently published by him in joint authorship with Eduard Brückner, he has given to the world the results of his investigations, and a complete account of all researches in the same direction up to date. This marvellous work is not only the ultimate authority on all questions connected with the glaciations of the Alps, but gives us a glimpse into what may possibly be effected when its exact methods and acute reasoning come to be applied to other districts.

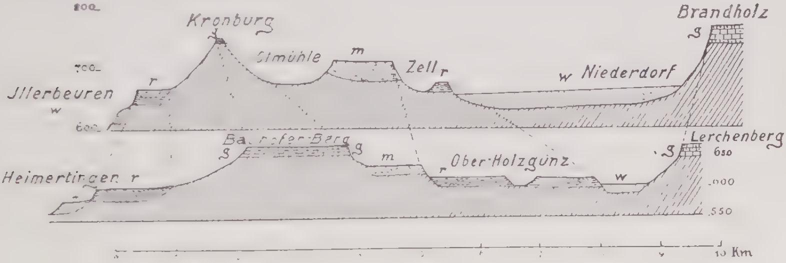

FIG. 43.—Sections showing the relations of the Quaternary gravels near Memmingen, Bavaria. (After Penck.)

g. Older Deckenschotter. *m*. Younger Deckenschotter. *r*. Higher terrace gravel. *w*. Lower terrace gravel.

It has long been known that in the moraine district of the Alpine foreland, just as in the case of the glacial drift of Northern Europe, there can be detected everywhere two belts of moraine, an outer or older belt and an inner or younger belt. These show a striking contrast in their surface features. The Young Moraine retains everywhere the form which it acquired on its deposition by the ice, and has not been seriously modified by subsequent denudation. The Old Moraine, on the contrary, shows a mature surface drainage, and is only recognisable as moraine by examination of the material of which it is composed. This contrast is strengthened by the fact that the Old Moraine has everywhere a cover-

Contrast between the Young Moraine and Old Moraine.

ing of loess or loam, which is completely wanting from the surface of the Young Moraine. A difference in age is thus clearly indicated similar to that between the older and newer drifts of the Northern Plain; and it is no great step thence to the conception of an interglacial period, to which the well-known inter-morainic plant-bearing deposits of the Alps, such as the "Höttinger Breccia" and the "Schieferkohlen" of Dürnten, Wetzikon, and Uznach, made famous by the researches of Oswald Heer, may be ascribed.

Fourfold repetition of the foreland glaciation proved by the outwash gravels.

The investigations of Penck and Brückner, however, have proved the occurrence of a more elaborate series of glacial and interglacial periods. This has been effected to a large extent by a consideration of the stacial outwash gravels, which gtretch away from the Alps along the courses of the outflowing rivers. These gravels can be subdivided into four series occurring at different heights above the present level of the rivers, and are known as

The Older Deckenschotter.
The Younger Deckenschotter.
The High Terrace Gravel.
The Low Terrace Gravel.

The Older Deckenschotter, of which only fragments are preserved, was spread out in great sheets on the peneplain which stretched in preglacial times away from the foot of the Alps. The Younger Deckenschotter forms similar sheets, which,

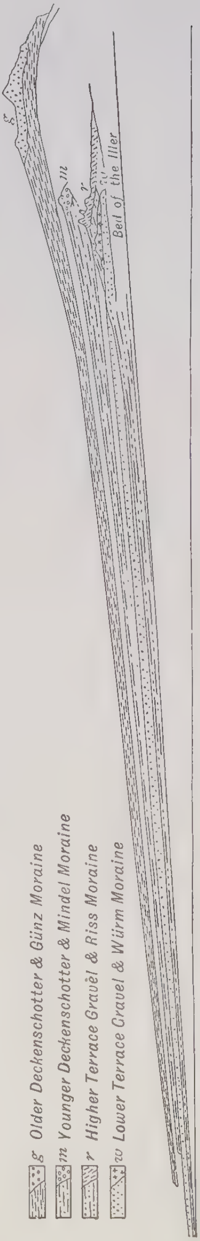
g
m
r
w
Bed of the Iller
g Older Deckenschotter & Günz Moraine
m Younger Deckenschotter & Mindel Moraine
r Higher Terrace Gravel & Riss Moraine
w Lower Terrace Gravel & Würm Moraine

FIG. 44.—Profile of the gravel terraces of the valley of the Iller, showing their relation to one another and to the moraines. (After Penck.)

however, are sunk in hollows eroded in the Older Deckenschotter. The two younger gravels form terraces along the rivers, and, being confined to the valleys, seldom take on the sheet form of the older gravels. The foregoing diagram (Fig. 43) of the gravels of Memmingen exhibits the relations very clearly.

The fluvio-glacial origin of these.

The fluvio-glacial origin of these gravels is beyond doubt. Followed up in the direction of the mountains they are each and all seen to be associated with moraines. Thus the Low Terrace is found to be clearly the outwash of the glaciation which formed the Young Moraine, the Higher Terrace and the Younger Deckenschotter are as obviously connected with the outer Old Moraine, the further subdivision of which is thus suggested, while the scanty remnants of the Older Deckenschotter can be traced in a few places within the district of the Old Moraine, and in rare instances its corresponding moraine can be identified. The source of the gravels thus being clearly established, it seems necessary, as Penck points out, to assume, corresponding to their fourfold repetition, a fourfold repetition of their origin, that is to say, of the glaciation of the Alpine foreland. Whether or not the greater part of the mountain mass was in the intervals between these epochs of glaciation free from ice, there is no doubt whatsoever that there were four distinct glaciations of the foot of the Alps. To these four glaciations Penck has given local names after places where their moraines and gravel sheets are well developed. They are in order of time:

The names of the glaciations.

The Günz Glaciation which formed the Older Deckenschotter.
The Mindel Glaciation ,, ,, ,, Younger Deckenschotter.
The Riss Glaciation ,, ,, ,, Higher Terrace.
The Würm Glaciation ,, ,, ,, Lower Terrace.

Differences between the gravels,

Now there are differences between these four gravels other than their relative altitude above the present river-system. The older gravels are much more firmly cemented and show deeper weathering than the younger. Moreover, when one of the older gravels underlies one of the younger its surface frequently shows weathering, and their relation to the loess,

indicating a lapse of time between their periods of formation. There is on the north side of the Alps a still further and even more remarkable fact pointing to their essential distinctness in point of age. This is that the gravel deposits of the first three glaciations are as a rule covered with loess, which on the other hand is completely absent from the Lower Terrace or gravel of the Würm Glaciation. In some cases the loess is confined to the surface of the fluvio-glacial gravels, and has at first sight the appearance of bearing the same relation to them as ordinary river-loam does to river-gravel. That it is a distinctly different deposit from the underlying gravel in its mode of origin is apparent, however, from the fact that it often rises on to the slopes

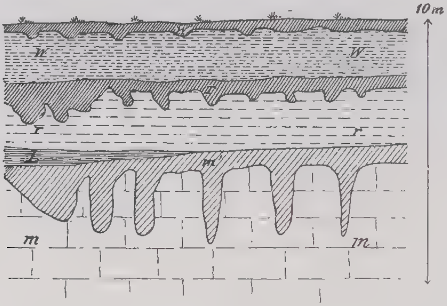

Fig. 45.—Section in a quarry near Deisenhofen, in the valley of the Gleissen, Bavaria, showing the weathered zones and loess between the outwash gravels. (After Penck.)

w'. Weathered, *w*. Fresh Lower Terrace Gravel. *r'*. Weathered, *r*. Fresh High Terrace Gravel. *m'*. Weathered, *m*. Fresh Munich Deckenschotter. *L*. Loess-loam.

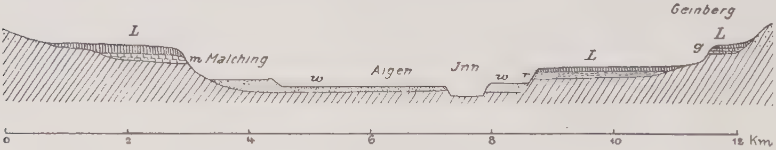

Fig. 46.—Section across the Inn Valley at Schärding, Upper Austria, showing the relative position of the gravels and their relation to the loess. (After Penck.)

g. Older Deckenschotter. *m*. Younger Deckenschotter. *r*. High Terrace Gravel. *w*. Low Terrace Gravel. *L*. Loess.

to a considerable height above the gravels, and covers great tracts of country where there is no gravel. It is also seen in many cases to overlie a weathered surface of gravel where it is itself quite unweathered, a fact which shows clearly that its deposition did not follow immediately on that of the gravel. Clearly it is the product of other agents than those which produced the gravels on which it lies, and no less clearly does it appear as a formation of distinctly later date than these gravels.

As has just been pointed out, typical loess occurs nowhere on the surface of the Lower Terrace, while it covers the adjoining Higher Terrace and stretches down to the edge of the Lower Terrace plain. This mutual exclusion of the two formations can be explained only on the assumption that the Lower Terrace is younger than the youngest loess, which was therefore formed in the Riss-Würm Interglacial Period.

which is proved to be a deposit of the Riss-Würm Interglacial Period,

This is, however, not the only period at which loess was formed, for it is found under the gravel of the High Terrace, and lying on the weathered surface of the Younger Deckenschotter. In other words, it is also a deposit of the Mindel-Riss Interglacial Period. Although there is no direct proof, it seems probable from analogy that loess was also formed during the Günz-Mindel Interglacial Period. It is at any rate clearly proved by its relations with the fluvio-glacial gravels of the Alps to be an interglacial formation, and to have been formed in at least two of the three interglacial periods.

but was also formed in the Mindel-Riss.

The investigation of the moraines on the north side of the Alps has confirmed the conclusions, arrived at from the study of the gravel fields, as to the fourfold nature of the glaciation. The last glaciation, that of the Würm Ice Age, has left behind it the feature of the Young End-moraine and its associated ground-moraine. These exhibit relatively little denudation and weathering, and are devoid of loess. The zone of weathered and loess-covered Old Moraine lying in front of the Young Moraine is the product of two Ice Ages, the Mindel and

These conclusions confirmed in the moraine district.

Riss. In comparison with the much-denuded moraine of the Mindel Ice Age the form of the Riss-Moraine is relatively well preserved. The establishment of the Günz Glaciation in the northern Alps depends almost entirely on the occurrence of the Older Deckenschotter, its moraines being here rarely preserved. They are, however, known in the districts of the Iller and Rhine Glaciers.

The absence of loess covering is thus a distinguishing character of the Würm-Moraine as well as of the Würm-Gravels, and the same may be said of its presence on the older moraines of the Mindel and Riss Ice Ages. Moreover, the loam into which it frequently passes has been found in the district of the Salzach Glacier interbedded between the moraines of the Riss and Würm Ice Ages, while near Bianne, east of Lyons, actual fossil-bearing loess occurs under the moraine of the Würm Ice Age. Its origin in at least one of the interglacial periods is thus proved in the moraine district as well as in that of the outwash gravels.

The fourfold classification found to apply all round the Alps.

The establishment of the fourfold repetition of the glaciation is a matter of such an essential nature, that it is important to note how completely this classification, established first in the northern part of the eastern Alps, has applied all round them. Between the Iller and Lech there occur four different gravels, each of which is separately associated with moraine. In the district of the Rhine Glacier the relations are again very complete, each of the four gravels passing here clearly into moraine. The same can be proved in the north-west of Switzerland. Four gravels occur also in the Rhone district about Lyons, and, although in the Durance district only three can be separated with certainty, still there are indications of a fourth. The fluvio-glacial origin of the three can be established at Schau. Finally, the Var Valley has afforded indications of four different gravels. In the Po district, also, four different gravels can be distinguished. The two younger contrast with the older weathered and iron-stained gravels, and there are not wanting indica-

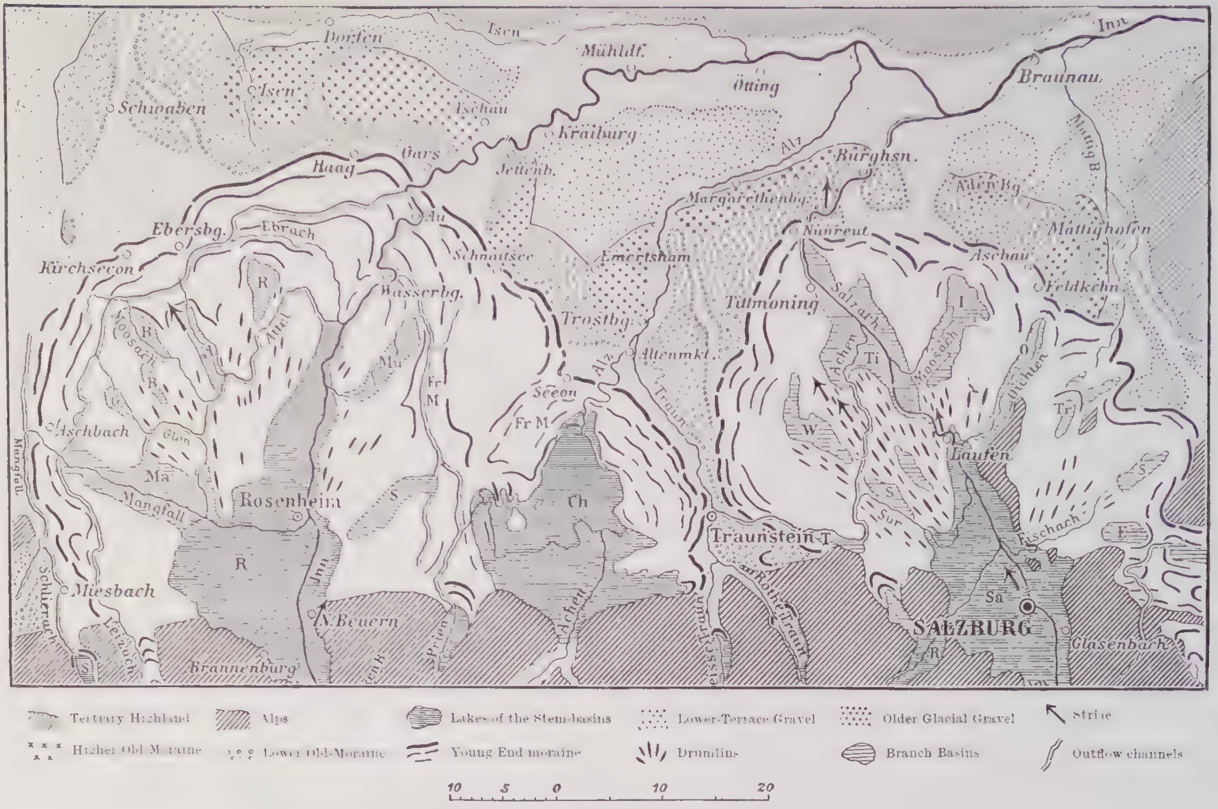

FIG. 47.—Map of the Inn and Salzach Glaciers. (After Penck.)

tions that the latter belong to two horizons. The relation of the two younger gravels in this district to the moraine is obvious, but that of the iron-stained gravels is not so clear. In the Insubrian district iron-cemented gravel was traced into iron-cemented moraine. In the Oglio only two fluvio-glacial gravels came to light, but on the south-west side of Lake Garda there are four distinct gravels, three of which can be traced into moraine. Four gravels were found in the Valmarino in the Piave district, two only in the Tagliamento and Isonzo district. The Save district, again, showed the regular sequence of four fluvio-glacial terraces. In the Drautal only two could be distinguished, but in the Klagenfurter Basin traces of three glaciations were found. The Murtal, which in general showed only two gravels, afforded in places the regular sequence of four. Having regard to the imperfection of the geological record in general, this evidence is considered sufficient to prove the occurrence of four glaciations.

The completeness of the interglacial retreat proved by intermorainic plant beds,

The separation of the gravels and moraines of four different glaciations carried out by Penck and Brückner has been effected in the periphery of the glaciated district, and from this alone it is only possible to deduce a fourfold glaciation of this outer belt and not of the whole Alpine district. A series of interglacial deposits have, however, been preserved which prove that at certain periods during the Ice Age the glaciers withdrew into the innermost recesses of the mountains. The more important of these are the "Höttinger Breccia" near Innsbruck, the "Schieferkohlen" of Dürnten, Wetzikon, and Uznach, the plant-bearing clay of Re in the Vigezzo Valley, and above all the beds of Pianico in the Iseo Valley. In addition should be mentioned the deposits of Flurlingen near Schaffhausen, of Entraigues in the Arvan Valley, and that of Calprino near Lugano. In these latter the plant-bearing beds are overlain by moraine, but the underlying moraine is wanting; there are other grounds, however, for believing that their deposition was preceded by a glaciation.

These interglacial deposits are presumed to belong to the last or Riss-Würm Interglacial Period, since the overlying moraine is that of the Würm Ice Age, and it is more probable that the beds belong to the immediately preceding interglacial period than to an older one.

which, on account of the importance of the conclusions depending on them, are described in detail.

Hötting Breccia.

The Hötting Breccia is a firmly cemented scree formation, the interglacial age of which was demonstrated by Penck in 1882. It is clearly overlain by moraine of the Würm Glaciation, and underlain by older moraine and glacial laminated clays. As doubt has been expressed as to whether these underlying glacial deposits are really older than the breccia, and not thrust in beneath them by the ice, it is important to note that Penck has now succeeded in proving them beneath the breccia in five distinct exposures extending over a distance of one kilometre. In another locality the breccia has been found to contain erratic material at an altitude of over 2200 m., proving that it was preceded by a glaciation at least as great as that of the succeeding Würm Ice Age. The plant remains, which were found in the Höttinger Quarries, do not lie along the bedding planes of the breccia, but traverse them obliquely as if suddenly overwhelmed. Of the forty-two species determined with certainty four are new, but possess near relatives among living plants. All the rest are still living, not a single one being known from the Tertiary. Of these, thirty of the species live at present in the neighbourhood. The only two of the remainder suited for drawing conclusions as to plant geography are *Rhododendron ponticum* and *Buxus sempervirens*, both of which are distinctly southern. One of the new species, *Rhamnus hoettingensis*, resembles the southern *Rhamnus latifolia* from the Canaries. There is a distinct relationship pointed out by Wettstein to the Pontic wood-flora which flourishes about 5° farther south in a district where the mean yearly temperature at sea-level is at least 3° higher than that of the district of Innsbruck. It is inconceivable that the Hötting flora could flourish where it was found at a height of 1150 m. over the sea under present climatic conditions. It presupposes a mean yearly temperature 2° higher than at present, and a position of the snow-line 400 m. higher. As it was formed between two glaciations, each implying a depression of the snow-line to the extent of 1200 m. below the present, it affords clear proof of an oscillation of sufficient amplitude to be regarded as interglacial.

Schieferkohlen of Dürnten and Wetzikon.

The interglacial "Schieferkohlen" of Dürnten and Wetzikon occur in the district of the Linth Glacier within 4½ km. of one another, and being situated in the same valley and at exactly the same altitude (540 m.), are presumed by Heer to belong to the same formation. In both exposures they are overlain by gravel, on top of which lies in turn the moraine of the Würm Ice Age. At Dürnten beneath the coal there occurs sand and loam with a mass of rolled stones, at Wetzikon a bright-coloured loam with fresh-water shells, and under this, moraine with striated Alpine boulders.

Of the eighteen species of plants found at Dürnten the most important for the purpose of drawing conclusions as to climate is the yew. At the present day, on the northern margin of the Swiss Alps, this never occurs over 800 m. altitude, and always keeps some 700 or 800 m. beneath the upper limit of trees. Hence at the time of formation of the Dürnten coal the wood boundary could not have been lower than 1300-1400 m., *i.e.* not more than 200-300 m. lower than at present. This requires a correspondingly small displacement of the snow-line, and shows that the climatic oscillation which led to the occurrence of the coal between moraines was of interglacial magnitude. The plants found at Wetzikon were much fewer, and do not include the yew. The mammalian remains at Dürnten, derived in part from the overlying loam, include *Elephas antiquus*, Falc.; *Rhinoceros merckii*, Jaeg.; *Bos primigenius*, Boj.; *Cervus elaphus*, L.; *Cervus alces*. The two first mentioned species are characteristic animals of the Riss-Würm Interglacial Period.

Schieferkohlen of Uznach.

The "Schieferkohlen" of Uznach were confidently regarded by Heer as equivalent to those of Dürnten and Wetzikon. They lie some 13 km. from Dürnten in another valley, but, curiously enough, at about the same altitude. The coal with its associated loam deposit is both overlain and underlain by moraine. The flora, however, as cited by Heer, was in no sense of interglacial character, the extinct and southern plants of Dürnten not having been found. The rather limited fauna, including *Cervus elaphus*, L.; *Bos primigenius*, Boj.; and *Ursus spelaeus*, Blumenb., pointed in the same direction, the typical interglacial mammals, *Elephas antiquus* and *Rhinoceros merckii* being absent. In view of these differences from the deposits of Dürnten, and having regard to the consideration that the overlying moraine is readily referable to the Bühlstadium, Brückner referred the Uznach deposit to the "Achenschwankung," thus making it interstadial instead of interglacial. Quite recently, however, Neuweiler has made a more thorough investigation of the flora, and proved that it is in every way comparable to that of Dürnten. In particular he pointed out that Heer's identification of *Pinus montana* from this deposit is by no means certain, and he obtained from it the yew (*Taxus baccata*). Neuweiler has, moreover, obtained from a neighbouring locality near Kaltbrunn a richer flora which belongs to the same horizon, and is of xerotherm character. As a result of these recent researches the deposit of Uznach, and with it that of Kaltbrunn, must now be regarded as interglacial. This is more in accord with the finding at Uznach of *Ursus spelaeus*, which, although it probably occurs in Magdalénien deposits in the Pyrenees, was certainly neither abundant in nor characteristic of the Post-glacial Period.

Schieferkohl of Mörswyl.

Heer has also described an interglacial "Schieferkohl" occurring between moraines at Mörswyl, on the southern shore of the Bodensee, in the district of the Rhine glacier. Indications of a warmer climate than the present are absent, but the occurrence of acorns shows, if the upper limit of the oak was at least as high at this period as now, that during the formation of the coal the snow-line lay at least 1000 metres higher than during the preceding and succeeding glaciations.

Plant-bearing clays of Re.

The plant-bearing clays of Re in the Vigezzo Valley, first investigated by Sordelli, occur associated with interglacial breccias. These latter are underlain by glacial gravel and moraine, and overlain by gravel of the Würm Ice Age. The stratigraphical relations of the actual exposure in which the plant remains were found not being determinable, the case is less directly satisfactory than others. According to Penck, however, a petrographical comparison with similar though unfossiliferous beds in the adjoining breccias leaves no doubt whatsoever as to the interglacial age of the deposit. The flora, as given by Sordelli, has, like that of the Höttinger breccia, a marked southern and south-eastern element which demands a higher position of the snow-line than the present. On the other hand, the finding by Bernassi of *Pinus montana* and *Salix reticulata* points in the opposite direction. This contradiction demands further investigation.

Lake deposits of Pianico.

More satisfactory are the interglacial beds of Pianico in the Oglio district. These are clearly old lake deposits dammed up by and overlying ground-moraine of the Riss Glaciation, and in turn overlain by Würm moraine. Towards the side of the valley the lacustrine clays dovetail into a calcareous breccia, which can be traced to a height of 380 m., and is overlain by moraine. The flora, which has been investigated by Sordelli, Fischer, and Amsler, is composed two-thirds of species living on the spot at the present day, and one-third of species with a south-easterly distribution. It is the typical Bosnian oakwood flora, such as is found also at Re, and does not ascend higher than within 2000 metres of the snow-line. The district of Pianico lay during the Würm Ice Age some 1400-1500 metres below the snow-line. The beds yielded *Rhinoceros merckii*, Jaeg., and *Cervus elaphus*, L.

Calcareous tufa of Flurlingen.

The calcareous tufa of Flurlingen, near Schaffhausen, in the district of the Rhine glacier, is overlain by moraine of the Würm Glaciation, and lies in a valley cut deep in the Younger Deckenschotter. It therefore belongs either to the Mindel-Riss or Riss-Würm Interglacial Period, more probably, of course, to the latter. The flora includes the box (*Buxus sempervirens*, L.) and sycamore (*Acer pseudoplatanus*, L.), the former of which does not occur at the present day near Schaffhausen, and has a south-westerly distribution. *Rhinoceros merckii* has also been obtained from the deposit.

Calcareous tufa of Entraigues.

The calcareous tufa of Entraigues, lying at 1200 m. in the Arvan Valley (Rhone district), is overlain by moraine, which, judging by the position of the snow-line necessary to its formation, cannot be younger than the Bühlstadium. The deposit is therefore probably referable to the Riss-Würm Interglacial Period. The flora is composed, with two exceptions, of species occurring in the neighbourhood at the present day. These exceptions are *Mespilus germanica* and *Carpinus betulus*, which do not at the present day reach this altitude and constitute a southern element.

Lake deposit of Calprino.

The interglacial clay of Calprino is an old deposit of Lake Lugano, formed when it lay at a much higher level. It is overlain by moraine of the Würm Glaciation, and yields plants of an interglacial character such as the Pontic rhododendron and the box. Although the locality lies 1400 metres under the snow-line of the Würm Ice Age, yet these plants exclude the possibility of the deposit being formed during a glacial period, as they require an even greater distance from the snow-line.

Older Interglacial Periods.

These interglacial deposits being all considered provisionally to belong to the Riss-Würm Interglacial Period, any conclusions drawn from them, strictly speaking, only refer to this period. By analogy it is inferred that conditions were somewhat similar in the Günz-Mindel and Mindel-Riss Interglacial Periods. No intermorainic deposits definitely referable to either of these periods are known, but in the " Schieferkohlen " of Leffe, in the Grandino Valley, which occurs under the high-terrace gravel, a plant-bearing deposit has been recognised which with great probability belongs to the second of these periods. The character of the flora of Leffe, with the walnut, horse-chestnut, and vine, is sufficiently like that of the typical interglacial formation, but the considerably greater number of extinct species speaks for a higher age.

The glacia and interglacial faunas.

These conclusions regarding the glacial and interglacial periods of the Alps are borne out by what is known of the Quaternary fauna. On the north side of the mountains are found two distinct faunas, an arcto-alpine fauna characterised by mammoth, woolly rhinoceros, and reindeer, and an interglacial fauna with *Elephas antiquus*, Merck's rhinoceros, and the red deer. With the exception that the red deer and reindeer are frequently found in association, intermingling of these faunas never occurs. Penck has established the twofold repetition of the arctic fauna and its separation by the interglacial fauna.

The older and younger glacial faunas.

The consideration of the numerous prehistoric finds of the Saône-Rhone District has contributed largely to this result. The older fauna was that of the Older Palaeolithic or Moustérien, the younger that of the Younger Palaeolithic or Solutréen and Magdalénien. The geographical distribution of the localities at which these faunas occur affords a basis for determining their relation to the glaciations. The *stations with the older fauna* are excluded by the district of the biggest Alpine glaciation. They extend right up to its border, but do not occur within it. From this it may be concluded that the older fauna was contemporaneous with the Riss Ice Age. *The stations with the younger fauna* can, on the contrary, be followed not only into the district of the Old Moraine, but also into that of the Young Moraine, where they perhaps first stop short at the moraines of that stage of retreat known as the Bühlstadium (see below, p. 155). This proves their contemporaneity with the Würm Ice Age. The finds in the loess assure us that this arcto-alpine fauna had already appeared before the maximum of the Würm Glaciation, while Magdalénien stations inform us that it somewhat overlasted this maximum.

The famous gravel terrace of Villefranche-sur-Saône possesses a considerable interest in this connexion. On stratigraphical grounds Penck has referred it to the Riss-Würm Interglacial Period. It contains Moustérien implements, but the fauna is of a mixed interglacial and arcto-alpine type, and has excited a good deal of controversy, some regarding the arcto-alpine element as washed in, others the interglacial. The case of the caves of Mentone on the south side of the Alps is more satisfactory. Here there is found not only an interglacial fauna with Moustérien implements, but also overlying this a deposit containing a fauna with arcto-alpine elements and remains of Younger Palaeolithic industry. This is unmistakable proof that the Moustérien industry is associated not merely with the arcto-alpine fauna of the Riss Ice Age, but also outlasted the same, and existed contemporaneously with the warm fauna of the Riss-Würm Interglacial Period.

The interglacial fauna.

On the south side of the Alps lie two important localities with an interglacial fauna. These are Pianico, which belongs to the Riss-Würm Interglacial Period, and Leffe in the Grandino Valley, which doubtless is older than the Riss Ice Age (see above, p. 140), and may with great probability be placed in the Mindel-Riss Interglacial Period. Both localities afford a warm fauna with red deer and Merck's rhinoceros. Palaeolithic implements, however, are wanting.

It is worthy of note that the deposit of Leffe, which, on account of its position beneath the high-terrace gravel and the greater number of extinct plants it contains, has been referred to the Mindel-Riss Interglacial Period, had yielded not only *Elephas antiquus* but also *Elephas meridionalis*. The latter can, therefore, no longer be regarded as exclusively Pliocene unless, indeed, the boundary between Pliocene and Pleistocene be placed in the middle of the Ice Age.

Inter-glacial conditions in the Alps. Wildkirchli.

The fossiliferous deposits of the Moustérien cave of Wildkirchli, in the Alps, recently described by Emil Bächler, are also to be referred to the Riss-Würm Interglacial Period. The cave lies on the east slope of the Ebenalp, at an altitude of nearly 1500 m. over the sea, and well above the upper limits of the Quaternary glaciation, during which the Ebenalp formed a nunatak. Its altitude is such that it could not have been inhabited except in a climate at least as mild as the present. Moreover, the great quantity of remains of the cave-bear (which Bächler concluded represented at least 1000 individuals) indicate a well-stocked hunting-ground, which is certainly inconsistent with any lower position of the tree line than that which it now occupies. The cave lies about 300 metres above the snow-line of the Würm Ice Age, during which it must clearly have been blocked with snow and stalagmitic ice, such as forms in the caves in winter at the present day. The deposits are thus referable only to a late stage of the Post-Würm Period or to the last Interglacial Period. The former supposition is excluded by the Moustérien type of implement found in them. The fauna, from which the arcto-alpine element is entirely wanting, includes the seven species, *Ursus spelaeus*, *Felis leo*, var. *spelaea*, *Felis pardus*, var. *spelaea*, *Canis lupus*, *Capra ibex* (the wild goat), *Capella rupicapra* (the chamois), and *Cervus elaphus* (the red deer). These all occur in the lower interglacial horizon of Mentone in company with *Elephas antiquus* and *Rhinoceros merckii* as well as Moustérien implements.

By the discovery of Wildkirchli we have learnt that there was in the last interglacial period a rich vegetation up to the present wood boundary, and that Moustérien man penetrated the Alps to this height. This evidence of vegetation is higher than that afforded by the plants of the Höttinger breccia.

Having thus set forth the evidence on which the conception of the fourfold nature of the glaciation is based, we will proceed next to consider the conclusions

Physiographical conditions of the Würm Ice Age.

arrived at by Penck and Brückner regarding the physiographic and climatic conditions of the Alps during the glacial and interglacial periods. These conclusions are based primarily on a study of the Würm Glaciation and the immediately preceding interglacial period, and are extended by analogy, with certain provable differences, to the older periods.

Determination of the Würm snow-line.

Of primary importance is the determination of the position of the snow-line during the Ice Age. This is effected by the consideration of certain small glaciers which had an independent existence apart from the general network, and is based on the experience that in valley glaciers of the present-day alpine type there are two simple relations connecting the position of the snow-line and the development of the glacier. The first of these relations is that the portion of the upper surface of the glacier lying beneath the snow-line bears to that lying above a proportion between $\frac{1}{3}$ and $\frac{1}{2}$. The second is that the mean height of the upper surface of the glacier is the height of the snow-line in the neighbourhood. Methods founded on these two relations give consistent results, and it has thus been found possible to map out the snow-line of the Würm Ice Age right round the Alps. The results show a peculiar relation to the present precipitation. In places where the precipitation is large the Würm snow-line was low. This was the case on the northern fringe of the mountains between the French Jura and the Austrian "Kalkalpen," on the southern border adjoining the Venetian plain, and on the eastern border on the Steiner Alps. The present precipitation of these three districts is relatively large. Where on the other hand the foot of the Alps lies in the rain shadow of the west wind, as in Piedmont and Styria, the snow-line of the Ice Age rises on the Alpine border to a height of 1800 m. From this close connexion between snow-line and precipitation it may be concluded that during the Ice Age the distribution of precipitation was similar to that of the present day, that in particular the west wind

Its relation to the present precipitation, was then as now the rain-bringer, and that, just as at present, the Adriatic richly supplied the south-east corner of the Alps with moisture.

and to the snow-line of the present day.

A further similarity becomes apparent when the snow-line of the Ice Age is compared with that of the present day. They both agree in rising everywhere from the border to the interior of the mountains, a phenomenon which is, of course, due to the outer hills having first distraint on the moisture-bearing winds. Localities where both snow-lines can be determined are rare, that of the Ice Age being best known on the border, and that of the present day in the interior of the mountains. In such places, however, there is nearly always a vertical distance of 1200 m. between the two. Consequently it must be concluded that they are parallel. An exception to this is found in the case of the Gurktaler Alps, where the present snow-line only lies about 800 m. over that of the Ice Age. These hills, however, are an area of small precipitation, being surrounded on all sides by higher mountains, which act as rain catchers. It is clear that a general depression of the snow-line in such a case as this must result in an increase of the precipitating power of the outer ring of mountains, and consequent further desiccation of the interior, the snow-line in which will, therefore, not be depressed quite as much as elsewhere.

The parallelism of the two snow-lines disproves the precipitation theory of the Ice Age.

From the general parallelism thus established it seems clear that an increase of precipitation can afford no explanation of the phenomena of the Ice Age. The height of the snow-line is, of course, largely determined by the amount of the precipitation, as appears from the fact that it descends lowest on those portions of the Alpine margin which are richest in rain. A general increase of precipitation ought to have exaggerated this local curving downwards, and the facts show that no such exaggeration took place. Another piece of evidence pointing in the same direction is that above the present snow-line the firn-basins do not seem to have been any fuller during the Würm Ice Age than they are at the present day. There are direct indications that no general increase of precipitation can have occurred, even accompanied by a fall of temperature. How absurd any explanation, which depends on a change of precipitation alone, really is, becomes apparent from the consideration that, to cope with the present ablation along the snow-line of the Ice Age, there must have been an annual snowfall equivalent to 11-14 m. of water. The climatic change which brought on the Ice Age was accompanied by a decrease in ablation rather than an increase in precipitation, and a decrease in the ablation is strongly suggestive of a general lowering of temperature.

Extent of the Würm Glaciation and position of the ice-shed.

In connexion with the fact that the firn-basins of the Ice Age, although more widely extended than at the present day, do not appear to have been any fuller, it is interesting to note the contrast drawn by Penck between the Quaternary glaciation of the Alps and that of Greenland at the present day. The interior of the latter country, as has been proved by the expeditions of Nansen and Peary, is an unbroken ice-sheet with a few isolated hills or nunataks rising above the ice near the marginal ring of mountains, through gaps in which great glaciers pour down to the sea. The Alps to the very centre supported only a meshwork of more or less connected ice-streams with ridges between, there being no continuous snow-field. In the more strongly glaciated districts, however, the glaciers of the north and south sides coalesced, and the ice-shed lay to the north of the water-shed, as is proved by the ice having flowed south over the Simplon, St. Gothard, and other passes.

Fauna of the Würm Ice Age.

The conclusions as to climate drawn from the development of the snow-line are in harmony with those derived from a study of the fauna and flora of the Würm Ice Age. The moraines are naturally devoid of fossils, but the gravels now and then yield animal remains. Isolated bones of various mammals are found. They represent members of an arcto-alpine fauna, which has a characteristic stamp through the presence of the mammoth (*Elephas primigenius*), the woolly rhinoceros (*R. tichorhinus*), and the reindeer (*Rangifer tarandus*). The two former are extinct, but their carcases have been found preserved in ice in the tundras of Northern Siberia, and they were provided with long hair as a protection from the cold. The reindeer at the present day is a typical tundra animal. All three indicate a considerably colder climate than the present.

Flora of the Würm Ice Age, and height of the tree-boundary.

Plant remains are wanting almost entirely in the fluvio-glacial gravels. They occur more richly in clay resting immediately on the slopes of the moraines of the last Ice Age. They belong to a typical tundra flora, and embrace elements which now find their richest development above the wood-boundary. The occurrences are rather rare, but suffice to show that the shrinking ice was not closely followed up by a rich plant growth, and that in the hollows 600-800 m. below the snow-line of the Ice Age trees did not occur. The wood-boundary on the north side of the Alps lay, therefore, during the Ice Age at least this distance below the snow-line.

A similar conclusion can be drawn from the close relationship which exists between the high Alpine and high northern floras of the present day, and from the occurrence of islands of both in the German "Mittelgebirge." These can have no other explanation than that there stretched once between the northern and alpine glaciations a connected district with an arcto-alpine flora which later followed the retreating ice. The tree-line must, therefore, have been sufficiently low to allow of such a general distribution of the arcto-alpine flora. The minimum vertical distance of 600-800 m. deduced from this fact, and from the fossil plant remains mentioned above, is the same as the distance between the snow-line and the tree-boundary in the Alps at the present day. The distance between snow-line and tree-line was, therefore, not decreased during the Ice Age. This is an important conclusion, for it appears that the tree-line is highest and the snow-line lowest in the regions of maximum precipitation, so that any general increase of precipitation during the Ice Age is excluded since it would clearly have reduced the distance between these two lines.

General aspect of the Alps during the Würm Ice Age; the tundras of the north, and the woodland of the south.

This knowledge of the wood-boundary gives an approximate conception of the appearance of the Alps during the Ice Age. On the north side the big foreland glaciers ended in a tundra-like desert, the margin of which lay only 400-600 m. beneath the snow-line. The broad gravel beds of the glacier-streams were, during the short summer, after the manner of the Icelandic *sandr*, traversed by numerous water-courses. The landscape presented similar features to that of the present day in the neighbourhood of the Vatnajökull, and just as in this locality the vegetation is sufficiently abundant in the neighbourhood of the ice to afford fodder for herds of cattle, so the tundras which lay on the margin of the northern foreland-glaciers of the Alps afforded food for the mammoth, the woolly rhinoceros, and the reindeer.

Quite different were the conditions on the south side of the Alps, where the snow-line lay considerably higher, and the larger glaciers extended so far beneath it that they must clearly have terminated in the forest-belt. Direct proof of this is rare. Only once have remains of the stems of trees been found embedded in moraine. The conditions must, however, have been very similar to those of Alaska at the present day, where the forest not only surrounds the glaciers, but extends on to their debris-strewn surfaces.

The big animals which grazed on the tundra of the north side were absent in the woodland of the south. Only in quite isolated cases in the plain of the Po have remains of the mammoth been found, whereas they are no rarity in the gravels on the north side of the Alps. The reindeer has only been traced southward on the west side of the Alps as far as Mentone; on the east side it only reached to Karst, and in the Po plain it was, like the woolly rhinoceros, apparently absent. The arctic element disappears here from the fauna of the

Ice Age, both because the Alps were an obstacle to its migration, and because the woodland of the plain of the Po did not afford it suitable conditions of existence.

The Riss Ice Age and its snow-line.

The Riss Glaciation, as we have seen, extended in general farther from the mountains than the Würm Glaciation. That the tongues of its glaciers were also thicker is suggested by the fact that at a few places within the mountains traces of an older glaciation have been detected above the limits of the Würm Glaciation. The difference is less than 100 m., and is confined to the periphery of the mountains, not having been observed in the centre. Here there is not the slightest evidence that the Riss was thicker than the Würm Glaciation. In this sense the relation of the Riss to the Würm is similar to that of the Würm to the present. The Riss Glaciation appears only as a tongue-swelling of the Würm Glaciation. This points to a lower temperature in the Riss Ice Age. A few places have afforded a chance of determining the depression of the snow-line for the Riss Ice Age. It is in round numbers 100 m. more than that for the Würm Ice Age.

Remarkable deduction regarding the absence of the Adriatic.

The rule that the Riss moraine extends everywhere beyond the Würm moraine finds an exception in the south-east corner of the Alps. From this it must be concluded that here the depression of the snow-line during the Riss Ice Age was not so great as elsewhere. Typically developed terraces, as for example in the Save district, leave no doubt of the occurrence of the Riss Glaciation here as elsewhere; and having regard to the fact that the terraces of the Riss Ice Age can be followed close up to the Würm moraine, it is inconceivable that a broad girdle of end-moraine has been eroded away. We must rather assume that the Riss Glaciation did not extend to the margin of the Würm Glaciation, and it is remarkable that this has been the case in that district which during the Würm Ice Age was characterised by exceptional lowness of its snow-line. This exceptional lowness was due to richness in precipitation, determined, as at present, by the neighbourhood of the

Adriatic. Is it possible, says Penck, that the sea can have lain farther away during the Riss Ice Age?

Mindel and Günz Ice Ages.

On the north side of the eastern Alps the Mindel moraines reach down into the sphere of the Riss moraines, and in the district of the Inn, Salzach, and Iller Glaciers the Mindel Glaciation was the greatest.[1] In the Rhine district, however, in Switzerland, in France, and in the Po district, the Riss Glaciation was the biggest. From this it must be concluded either that the depression of the snow-line in the northern part of the eastern Alps was greater than elsewhere, or that the height relations have altered in such a way that the district, in which the Riss Glaciation descended below the Mindel Glaciation, underwent an elevation in the Mindel-Riss Interglacial Period. Such an elevation, to the extent of at least 150 m., has been proved independently for Switzerland by Brückner from a consideration of the tilting of the preglacial plane at the foot of the Alps. If this conclusion is right, and if a considerable part of the Quaternary Alpine elevation, of which there are many indications, fell in the Mindel-Riss Interglacial Period, then it is clear that the big extent of the Riss Glaciation in comparison to the Mindel Glaciation must be partly referred to an elevation coming in between, and at the same time it must be assumed that the biggest depression of the snow-line occurred in the Mindel Ice Age.

The Günz Ice Age has left its main traces in the form of fluvio-glacial gravels. Its moraines are rare, but can with certainty be proved in the Iller and Rhine Glaciers. They lie everywhere within the boundaries of the Würm Glaciation.

Inter-glacial flora of the Alps.

In striking contrast to the condition of the Alps during the Würm Ice Age stands the picture suggested by the interglacial flora. In Switzerland this closely agrees with the present flora. Here at 400-600 m. over the sea the forest trees which also prevail at the present day, namely, the silver fir, spruce, Scots fir, oak, maple, birch, and hazel, occurred also in the interglacial period. The occurrence in addition of the yew and box, as well as of *Brassenia purpurea* and *Trapa natans*, entirely excludes the idea that the snow-line could then have been lower than at present. On the south side of the Alps the interglacial flora has, on the other hand, a marked Illyrian stamp. The sweet chestnut occurred up to 400 m., the height of the wood-boundary in the Würm Ice Age. The vine throve, as at the present day, at the edge of Lake Iseo. The box was widely distributed as well as the large flowered Pontic rhododendron, which at the present day is foreign to the Alps. This shrub played also a considerable rôle in the interior of the Alps, and flourished at Hötting at an altitude of 1150 m.

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[1] This does not, however, hold for the Isar Glacier which lies between them. Here the Riss Glaciation was the biggest. This is connected with the fact, proved by the erratics in the moraine, that the Isar Glacier, during the Mindel Ice Age, was fed to a much less extent by the Inn Glacier, the doors by which the feeding took place not being yet sufficiently open.

Thus the northern foot of the Alps was occupied during the interglacial period by the typical forest of the Baltic, the south by that of the Illyrian botanical region, and the interior up to 1500 m. also by plants of a south-eastern stamp. There is not the slightest intermingling of any traces of an arcto-alpine flora such as later on extended itself in the Würm Ice Age to the north foot of the Alps.

Glacial and interglacial faunas contrasted.

To the difference in the floras of the glacial and interglacial periods corresponds an equally striking difference in the faunas. Instead of the mammoth (*Elephas primigenius*) occurs *Elephas antiquus*, instead of the woolly rhinoceros (*Rhinoceros tichorhinus*) Merck's rhinoceros (*R. merckii*), and instead of the reindeer the red deer. *Elephas antiquus* has not been found on the south side of the mountains.

Fossils of the loess.

Reference has already been made to the interglacial relations of the loess in the neighbourhood of the Alps. It remains to consider to what extent its fossil contents agree or contrast with those of the deposits just discussed. The evidence available is not very satisfactory, as plant remains are almost entirely wanting. The fauna, however, betrays, according to Penck, no interglacial character, but shows on the contrary the arcto-alpine elements of the Ice Age fauna. Moreover, the Palaeolithic instruments contained in the loess are so closely related to those which belong to the end of the Würm Ice Age, that the loess cannot possibly be much older. The explanation is probably that the loess is essentially younger than the typical interglacial deposits, and its formation was associated with the growth of the glaciers of the Würm Ice Age. The thick wooding of the interglacial period would, in fact, be adverse to the production of loess, which, as far as we know, is only possible in a district of thin vegetation. On the other hand, its formation is clearly not an essential accompaniment of glaciation. Below Lyon in Provence and in the Po plain there is no actual loess, nor does any occur on the whole eastern foot of the Alps. During the Ice Age these districts were, as we have seen, thick woodland, while those on the north side of the Alps, in which the loess shows its most important development, were above the wood-boundary. The distribution of the loess, therefore, does not contradict its formation during a glaciation.

Pointing in the same direction we have the further fact that the loess north of the Alps shows its greatest development in the valleys by which the drainage-waters of the glaciers made their way to the sea, *e.g.* along the Danube and the Rhine, and along the Rhone down to where it flowed into the wood district of the Ice Age. It remains, however, to be explained why the loess is absent from the moraine and gravel of the Würm Ice Age. The climatic conditions during the advance of the ice appear to have been very different from those which prevailed during its retreat.

Duration of the Ice Ages.

It is very difficult to form any idea of either the absolute or relative duration of the four Ice Ages. The maximum, as is most clearly seen in the case of the

Würm Ice Age, appears to have been maintained for a fairly long time, to judge by the great quantity of material accumulated in the end-moraines, outwash fans, and drumlin belt. The moraines of the Riss Ice Age are even more bulky than those of the Würm. Its duration was therefore, according to Penck, in all probability greater than that of the latter. The same may be said of the Mindel Glaciation. Moreover, if the bulk of the outwash gravels, when reconstructed in imagination from their remnants, be any indication of the length of the glaciation, then the Günz Glaciation must have been the longest of all. It must, however, be confessed that there are considerable elements of doubt in estimates of this type.

Relative duration of the Inter-glacial Periods.

An estimate of the relative duration of the interglacial periods Penck seems to regard with greater confidence. He considers that the sum of the geological work which is concentrated in the Mindel-Riss Period is so much greater than that of the Riss-Würm Period, that we are forced to the assumption of a highly improbable increase of denudative power in the former if we suppose them to have been of equal length. This difference expresses itself as follows :

(1) Everywhere round the Alps where the gravels of the Ice Ages occur in terraces, the two older are considerably higher than the two younger, and separated from them by an outcrop of older rocks. No such gap occurs between the gravels of the two last Ice Ages. The valley formation between the Mindel and Riss was much greater than that between the Riss and Würm.

(2) When the gravel and moraine of the two older Ice Ages are seen in section under those of the two younger, they are much more strongly cemented and weathered.

(3) When the moraines of the Mindel Ice Age occur at the surface they are much more denuded than those of the Riss and Würm, having lost, in fact, any trace of their original form.

(4) There are many old valley bottoms preserved referable to the Mindel-Riss, none to the Riss-Würm.

(5) In the Klagenfurter basin the deposits of the Mindel-Riss are much greater than those of the Riss-Würm.

From these data in general, but more particularly from the intensity of the weathering of the Munich Deckenschotter beneath the gravel of the Riss Ice Age in comparison with the weathering of the latter under the Würm gravel, Penck concludes that the relative durations of the two periods were as 4 to 1.

On the same principle of regarding denudation and weathering as a measure of time, the Riss-Würm Interglacial Period must have been considerably longer than the whole time which has elapsed since the Würm Ice Age. The Würm moraine is remarkably fresh, its form being practically unaltered. On the other hand, the Riss moraine has to a large extent lost its form. The arrangement of its ridges still betrays its origin as end-moraine, but all the small furrows and pot-holes, which in a capricious manner characterise the young end-moraine landscape, are wanting on it. This difference is expressed in the long current terms "Young Moraine" and "Old Moraine." The Old Moraine has a strongly weathered surface which can be traced under the Young Moraine. The latter is almost unweathered. The outwash gravels exhibit similar relations, and sometimes slightly weathered gravels of the Low Terrace can be seen resting on strongly weathered gravels of the High Terrace, as, for example, in the district of Munich and on the Oglio. From the exposures at Munich, Penck estimates the durations of the Riss-Würm and Post-Würm Periods to be as 3 to 1.

No evidence is available for determining the relative length of the Günz-Mindel Period, except the fact that the two higher gravels lie together like the two younger. From this its duration is assumed to be the same as that of the Riss-Würm Period. All the results put together give the following proportions:

Günz-Mindel.	Mindel-Riss.	Riss-Würm.	Post-Würm.
3	12	3	1

No comparison can, of course, be drawn between the glacial and interglacial periods.

Double character of the Würm end-moraine.

The terminal moraine of the Würm Glaciation is for the most part double, consisting of two wreaths, one of which lies within the other. In the Tagliamento Glacier in Switzerland and in the Drau district a third moraine-wreath can also be separated. The possibility that the formation of the inner of the two main wreaths was preceded by a period of lesser extent of the glaciers (the "Laufenschwankung"), and marks the end of a readvance, is discussed by Penck, but the evidence for this oscillation is not regarded as conclusive. It appears to depend mainly on occurrences of sand and gravel beneath the moraine of the Würm Glaciation.

Stages of retreat.

Between the outer girdle of Young Moraine and the present glaciers there occur repeated isolated end-moraines, which indicate a stationary state of the ice, that is to say, a break in the retreat of the Würm Glaciation. They are named by Penck retreat-stadia ("Rückzugsstadien"), but it is considered probable that they were formed at the end of periods of readvance. The moraines appeared at first sight to be irregularly distributed, but investigations on the northern side of the eastern Alps showed that they fall into three important groups, corresponding respectively to elevations of the snow-line of 300, 600, and 900 metres above that of the maximum of the Würm Ice Age, or, what is the same thing, to depressions of 900, 600, and 300 m. below the present snow-line. To these stadia Penck has, following his custom, given local names after places where the moraines corresponding to them are remarkably developed; they are:

The Bühlstadium	corresponding	to a	snow-line	900 m.	below	the present.
The Geschnitzstadium	,,	,,	,,	600 m.	,,	,,
The Daunstadium	,,	,,	,,	300 m.	,,	,,

This separation has also been proved to hold true in Switzerland. Here it appears that of 65 stadia investigated 5 belong to a snow-line of 850-950 m., 22 to one of 550-650 m., and 24 to one of 250-350 m. below the present snow-line. That is to say, that in this district also four-fifths of all the cases considered grouped themselves about the mean numbers of 900 m., 600 m., and 300 m., which were arrived at in the eastern Alps. An investigation of the stages of retreat in the Etsch district has shown that three main stadia can also be distinguished there.

It is only the smaller glaciers for which the depression of the snow-line can be readily determined according to the rules stated on p. 144, for their stages of retreat are marked by clear end-moraine walls. In the bigger Alpine valleys the moraines of retreat are frequently strongly eroded and difficult to trace, and even where they can be traced the determination of the corresponding snow-line is of course impossible. Nevertheless, in many of the big valleys end-moraines can be distinguished which are referable with a fair degree of certainty to the Bühlstadium.

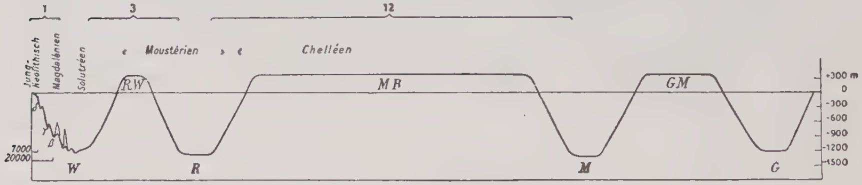

Fig. 48.—Climate curve of the Ice Age as recorded in the Alps. The figures across the top represent the supposed relative length of the post-glacial and interglacial periods, those on the right of the figure the height of the snow-line referred to that of the present day as zero, and those on the left, with the accompanying lines, the estimated age in years of the post-glacial stadia. The Aurignacien Period should be shown between the Solutréen and Moustérien. (After Penck.)

Inter-stadial periods.

The answering of the question how far the stages of retreat were marked by readvance depends on the possibility of proving interstadial formations. It is, of course, extremely difficult to distinguish between interstadial and interglacial. This can only be done with certainty when the flora of the deposit in question indicates an oscillation of the snow-line of too great a magnitude to be regarded as interstadial. Penck has adopted the temporary expedient of regarding all such deposits as interstadial which are not either in this manner or by stratigraphical considerations proved to be interglacial. He has thus come to consider that there were probably two important interstadial periods, of which one, the "Laufenschwankung," referred to above, occurred during the maximum of the Würm Glaciation, and the other, the "Achenschwankung," preceded the Bühlstadium. It is admitted, however, that the reference of certain deposits to these periods is by no means without doubt, and that, more particularly, the existence of the Laufenschwankung cannot be regarded as proved.

The younger stadia, the Geschnitzstadium and Daunstadium, are regarded also as being accompanied by readvances of the glaciers, since their moraines often rest on gravel floors. More particularly in the case of the Daunstadium a readvance has been proved, by the occurrence on the Col de Lauteret near Briançon, beneath its moraine, of a bed of calcareous tufa, containing a flora which indicates a position of the snow-line at least as high as that of the present day. There thus appears to have been a distinctly milder period between the Geschnitzstadium and the Daunstadium.

Minor climatic oscillations.

From a consideration of the retreat-stadia it becomes, therefore, apparent that the climatic curve of the Ice Age (see Fig. 48) exhibits in the Post-Würm Period no steady transition from glacial conditions to those of the present day, but on the contrary describes marked oscillations. By analogy it becomes probable that throughout the Ice Age the larger oscillations of glacial and interglacial magnitude have been interfered with by smaller oscillations, of the amplitude of which we have no very definite knowledge.

Estimate of post-glacial time.

Estimates of geological time from considerations of denudation and deposition are at the present day regarded with much distrust, and Penck, although he puts forward some figures, makes it clear that they are only to be regarded as an indication of the magnitude of the periods involved. The greatest doubt exists, of course, concerning the older periods, for we do not know to what extent the processes of denudation and deposition may have been accelerated under glacial or interglacial conditions.

According to the estimates of Heim on the growth of the Muota delta in Lake Lucerne, the period elapsed since the formation of the Bühl-moraine runs to about 16,000 years; and if, as there are grounds for assuming, the Magdalénien settlement on the Schweizersbild is not older than the Bühlstadium, then the latter, to judge by the estimates of Nüesch for the absolute age of this station, is to be dated back at least 24,000 years. A period of 16,000 to 24,000 years since the Bühlstadium can by no means be regarded as too long, since it appears that the Middle-European Copper Period (= Younger Neolithic) is younger than the Daunstadium, so that the latter must be back at least 4000 to 4500 years. The Younger Neolithic or Copper Period, like the entire Metal Period in the Swiss pile-dwellings, appears to have occurred under present climatic conditions, and there is not the least reason to suspect, either during or since it, any climatic oscillation of the magnitude of that of the Daunstadium. This stadium must, therefore, be dated back before the Swiss pile-dwellings, or in round numbers 7000 years ago.

Thus we have roughly—

Since the	Daunstadium,	7,000 years	
,,	Bühlstadium,	20,000 ,,	(mean of 16,000 and 24,000)

Penck discourages any stress being laid on the fact that one of these periods is roughly three times the other, and merely draws the conclusion that the Post-Würm Period must have lasted considerably over 20,000 years. Using the comparative durations deduced above (p. 154) from considerations of denudation, he obtains—

For the absolute duration of the Riss-Würm Interglacial Period about 60,000 years.

For the absolute duration of the Mindel-Riss Interglacial Period about 240,000 years.

And he points out that the immense thickness of the Quaternary deposits of the Po plain seems to confirm these results.

CHAPTER VIII

THE GLACIATION OF NORTH AMERICA

Extent of the American Ice-sheet—The three centres of dispersal—Eastward shifting of the area of maximum accumulation—Older and newer drift-sheets—The Kettle Moraine—The older or extra-morainic drift-sheets—Kansan—Illinoian—The Yarmouth overlap—The Iowan drift-sheet and its relation to the loess—The Sangamon soil-horizon—The intra-morainic drifts—The earlier and later Wisconsin drifts—The Peorian soil—The Toronto interglacial period—Scheme of classification.

Centres of accumulation.

HUGE as was the European Ice-sheet, that of America was immensely greater. It covered an area of 4,000,000 square miles, and spread its ground-moraine as far south as the 38th parallel, 12° farther south than that of Europe. As in the case of the European Ice-sheet, the flow from the several centres of dispersal attained a maximum at different periods. One of these centres of accumulation and dispersal lay in the western mountains, and is known as the Cordilleran; the remaining two, the Keewatin Centre and the Labradorean Centre, occupied comparatively low grounds respectively west and east of Hudson's Bay. The ice-sheets which spread out from these centres are for brevity referred to by the same names.

Satisfactory evidence has been put forward to prove that the Cordilleran Ice-sheet reached its maximum development before the Keewatin, and the Keewatin before the Labradorean. There is, however, some difference of opinion regarding the lapse of time between the successive developments. Tyrrell, for instance, has suggested that the Cordilleran sheet had almost entirely retreated before the Keewatin sheet invaded the area formerly occupied by it, and that the Keewatin in its turn, after reaching its farthest development, had shrunk

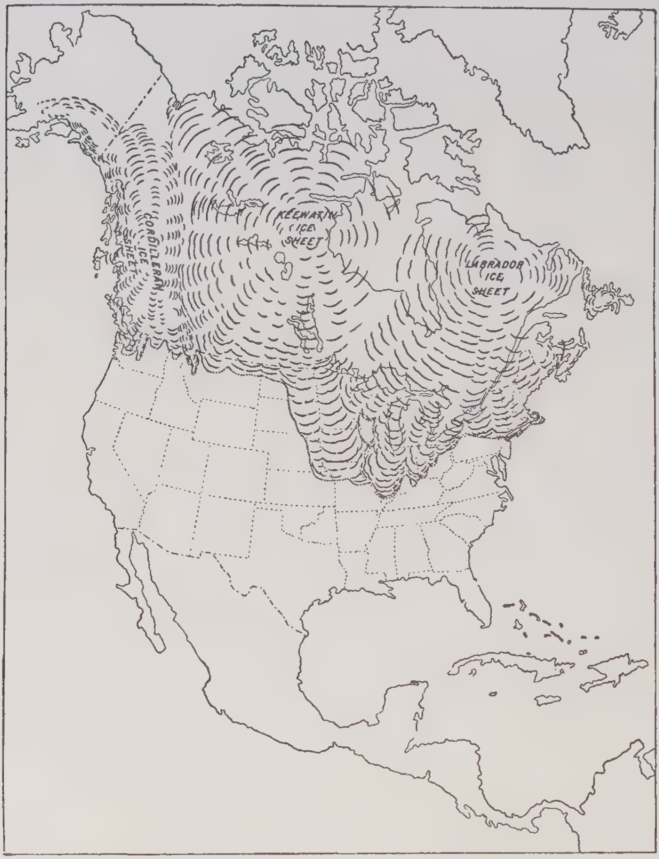

Fig. 49.—Sketch map showing the centres of radiation in North America. (After Chamberlin and Salisbury.)

half-way back to its central gathering ground before the main advance of the Labradorean ice. It is, however, not improbable that the ice-sheets were more nearly contemporaneous than he supposed, and came in contact along their margins, a certain amount of debatable ground being occupied first by one sheet and then by the other.

However this may be, it is at least certain that the area of maximum accumulation of ice on the American continent shifted from west to east during the Ice Age. Thus both in Europe and North America the displacement appears to have been in the direction of the North Atlantic, and it has been more than once suggested as a cause of this phenomenon that the growing ice-sheets intercepted, on their Atlantic slopes, the moisture-laden winds from the ocean.

Eastward shifting of the maximum.

A further point of resemblance between the glaciation of Europe and America is the contrast between the far-spreading older drift-sheets and the newer drift which lies nearer in towards the centres of dispersal. In America as in Europe the older drift is remarkable for its absence of topographic expression. Moraines, kettle-holes, drumlins, eskers, and other features of glacial topography such as abound on the newer till-sheets, are almost if not entirely wanting on this outer area occupied by the older drift. The latter exhibits, moreover, a maturity of drainage in marked contrast to the almost completely uneroded character of the newer drift. Finally it is extensively covered with a thick coating of loess which rarely encroaches upon the inner sheet.

Older and newer drifts contrasted.

The great Kettle Moraine of the United States marks the southern limit of the newer or Wisconsin till-sheet. It forms the boundary between what are known as the intra-morainic and extra-morainic drifts. The older extra-morainic drift, though everywhere characterised by its subdued topography and relatively advanced state of erosion, is by no means all of the same age. It has been proved to embrace at least three sheets deposited in succession to one another. These are known respectively as the Kansan, Illinoian, and Iowan drift-sheets. The Illinoian sheet overlaps the Kansan, and the Iowan overlaps both the Illinoian and Kansan. Chamberlin has attempted to distinguish a still older sheet which he calls the sub-Aftonian, but the evidence for it is

The great Kettle Moraine.

fragmentary and can hardly be considered of a satisfactory nature.

The Kansan drift.

The *Kansan Till-sheet* occupies a large surface area in Kansas, Missouri, Iowa, and Nebraska. It is in these districts considered to be a product of the Keewatin Ice-sheet only, the equivalent product of the Labradorean sheet being as yet unidentified. There is a remarkable scarcity of water-assorted material either in, on, or leading away from the edge of this drift-sheet, a point the significance of which in glacial theory can hardly be overestimated. That an enormous ice-sheet can thus be

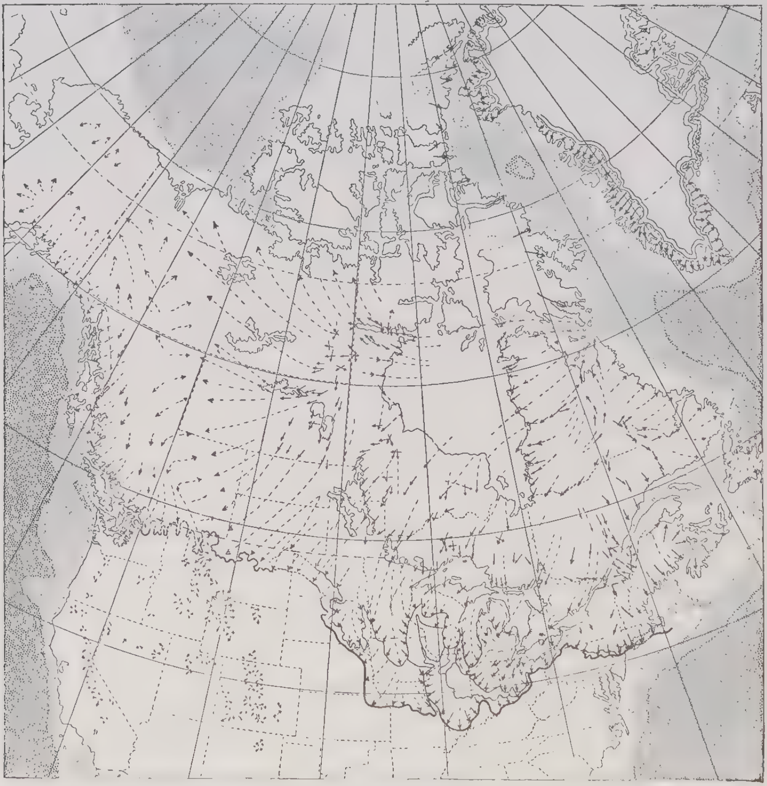

Fig. 50.—Map of North America, showing the trend of the glaciation and the form of the ice lobes at various stages. (After Chamberlin and Salisbury.)

dissipated without any great production of water as a product of its melting is, as pointed out by Chamberlin, one of the strangest of all the strange phenomena of the glacial period.

The Kansan till-sheet has suffered considerably greater erosion than the younger drift. Where it is overlapped by the Illinoian in the neighbourhood of the Mississippi this is especially marked, showing that a large part of the denudation of the Kansan drift took place before the exposure of the Illinoian. This inference is supported by the deep weathering of the Kansan drift and the pronounced decay of its boulders.

The Illinoian drift.

The *Illinoian Till-sheet* occupies the southern and western portions of Illinois and the south of Wisconsin. It is traceable as the surface deposit into Indiana and Ohio, but farther east it was overridden by the ice of the Wisconsin epoch. It is a product of the Labradorean Ice-sheet, its equivalent in the Keewatin area being at present unknown. There is a notable scarcity of associated water-sorted material, but this is not quite so marked as in the case of the Kansan drift. It is, as stated above, somewhat fresher, and also less eroded than the Kansan till, and as this difference in the amount of erosion and weathering has been cited by Chamberlin as proof of an interglacial period, the Yarmouth Period, between the deposition of the two sheets it will be well to consider more closely the relation of these sheets, especially in the region of overlap.

The Yarmouth overlap.

The Kansan till was deposited by a lobe of ice which pushed south along the western side of the driftless area of Wisconsin, and the Illinoian by a similar lobe which advanced along the eastern side of the same area. To the south, beyond the driftless area, occurs a region of overlap which was occupied first by the Kansan sheet, and later by the Illinoian, so that the ground-moraines of the two sheets are found here in superposition. This area of proved overlap is about 25 miles broad and 100 miles long, and in numerous well sections throughout its extent old soils and beds of peat, often containing fossil wood, have been found intercalated between the two sheets of boulder-clay. The following section[1] at Davenport, Iowa, may be regarded as typical:

Loess	30 feet
Leached and stained Illinoian till	3 ,,
Characteristic Illinoian till	15 ,,
Gummy clay with black streaks	3 ,,
Characteristic Kansan till, surface eroded	25 ,,
	75 feet

There is, therefore, good evidence pointing to a considerable lapse of time between the abandonment of Iowa by the Kansan lobe of the Keewatin Ice-sheet, and the invasion of Illinois by the Illinoian lobe of the Labradorean Ice-sheet, the length of this interval being indicated by the intercalated soil and peat of the area of overlap. That this lapse of time is at all represented by the difference in erosion between the Illinoian and Kansan drift-sheets, as upheld by Chamberlin, is, I think, not so obvious, since a great part of the erosion of the Kansan sheet may have taken place while the Illinoian ice was in occupation of Illinois. In short, the difference in weathering and erosion is not a measure merely of the length of the Yarmouth Period, but of the combined Yarmouth and Illinoian Periods.

With regard to the climate indicated by the Yarmouth beds little is known. Chamberlin and Salisbury think that the finding in them of bones of the rabbit and skunk indicates conditions not essentially different from the present. It cannot, however, be justly contended that this meagre and climatically unrepresentative fauna is sufficient ground for the drawing of any such conclusion. To ascribe to these beds an interglacial significance, implying thereby that the ice vanished from North America, or even withdrew from the United States, is going entirely beyond the evidence. The Yarmouth beds merely mark an interval between the Kansan and Illinoian ice invasions, and it is still open to any one to consider these invasions as episodes of a single glaciation. That one should be later than the other is a natural outcome of the clearly proved later development of the Labradorean Ice-sheet.

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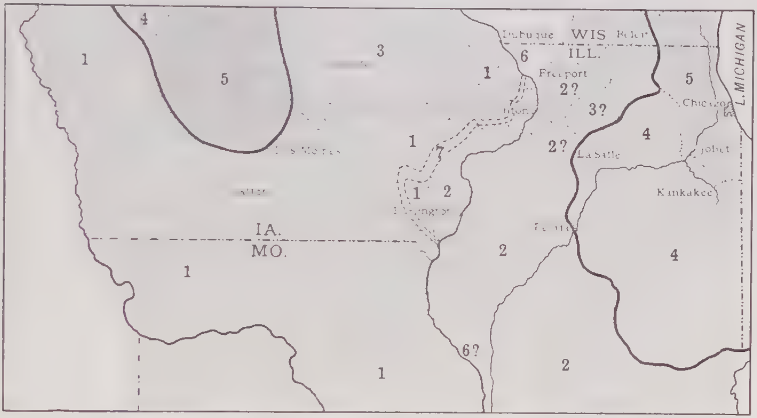
[1] Leverett, "The Illinois Glacial Lobe," Monograph xxxviii., *U.S. Geol. Surv.* p. 45.

The typical *Iowan Drift* is a thin sheet of till formed by a lobe of the Keewatin Ice-sheet, and occupying the north-central part of Iowa. The tendency to morainic ridging is, as in the case of the Kansan and Illinoian, very feeble, and the outwash from the border was also slight. The Labradorean equivalent is not definitely known, but is supposed to be represented by a drift-sheet in northern Illinois apparently much younger than the Illinoian till. The chief interest of the Iowan drift is its relation to the loess, which is very thick immediately beyond its margin, and overlaps it only for a short distance. This relation holds also for the supposed Iowan of Illinois. The association has been taken as proving that the loess is largely of Iowan age. Its

The Iowan drift.

Its relation to the loess.



Emery Walker sc.

FIG. 51.—Map showing the relations of the several drift-sheets in Iowa and northern Illinois. (After Chamberlin and Salisbury. The line separating the Wisconsin from the older drift has been thickened in order to bring out the relations more clearly.)

1. Kansan. 2. Illinoian. 3. Iowan. 4. Early Wisconsin. 5. Late Wisconsin. 6. Driftless area. 7. Course of the Mississippi during the Illinoian glacial epoch.

thickness along the border of this drift-sheet, combined with its absence from the interior of the sheet, certainly point to its being chiefly formed before the area of the Iowan drift was finally abandoned by the ice. The overlap at the margin indicates that loess formation continued at least until the beginning of this retreat. The relation is important since Leverett has founded his so-called Sangamon Interglacial Stage on the supposed contemporaneity of the loess and the Iowan drift. The term Sangamon was introduced by him to denote " a definite soil horizon between the Iowan loess and the Illinoian till-sheet," the loess being assumed to be of Iowan age, and its deposition intimately connected with that of the Iowan drift-sheet. Now, the proof of the Iowan age of the loess depends, as already stated, solely on the fact that it stretches in force up to the margin of the Iowan drift, and there practically stops short, being very thick just outside the drift margin, and only overlapping it for a short distance. This relation, especially the overlap, certainly shows that the loess is in part at least of Iowan age. To what extent it is coextensive with the Iowan glaciation in point of time it is impossible to say. It may only coincide with a portion of the Iowan glaciation, and on the other hand it may be largely pre-Iowan. It cannot, therefore, be considered sound reasoning to regard the pre-loess soil as evidence of an interglacial period. No identifiable fossils have been obtained from it, and there is no evidence of any retreat of the ice during its formation. At Stratford, 5 miles east of Polo, however, the railway cutting exposes, according to Leverett, a bed of fossiliferous silt with *Succinea avara*, overlain by Iowan till, and resting on an old land surface formed on the Illinoian. Two beds of similar silt occur beneath the Iowan in Boom County. For some reason Leverett does not correlate these Succinea-bearing silts with the loess. Whatever they are they may possibly be indicative of a certain amount of pre-Iowan retreat. Apart from these occurrences the Sangamon soil lies entirely outside the

The Sangamon stage.

Iowan drift-sheet, and its organic remains yield no evidence that it could not have been formed in the neighbourhood of an ice-sheet. The recognition of this soil horizon is a matter of the utmost importance, but it cannot with any confidence be regarded as having the interglacial significance attached to it by Leverett.

Recent views on the Iowan question.

Of recent years, however, a doubt seems to have grown up in the minds of American glacialists concerning the Iowan drift. Calvin, who originally separated this drift-sheet, and considered the loess to have been contemporaneous with it, now appears to regard the latter as of interglacial age and post-Iowan. Leverett, who was responsible for the separation of the 'Iowan' of Illinois, has since studied the original Iowan of Iowa, and maintains that it does not differ either in material, weathering, or degree of erosion from the surface of the Illinoian. He also has come to regard the loess as of interglacial age. From either of these points of view the exclusion of the loess from the surface of the Iowan drift remains unexplained.[1] It is interesting to note that the apparent ease and definiteness with which the Americans have read the record of their glacial deposits is gradually becoming reduced to a state of agnosticism very similar to that of the European glacialists towards their northern drifts.

The three till-sheets already described belong to the older or extra-morainic drift. All are characterised by a monotonous uniformity in their surface features, and a scarcity of associated water-sorted material. They differ in this respect greatly from the newer drift which lies inside the Kettle Moraine. Here we find great surface relief and abundant water-sorted material. The contrast between the two types of topography cannot be too strongly emphasised, for it indicates a difference in the mode of retreat of the ice which is one of the most significant facts in glacial geology.

The Wisconsin drift.

The *Wisconsin* or intra-morainic drifts occupy a large area in the Northern States and in Canada, being nowhere overlapped by later drift. They have, as has just been pointed out, in striking contrast to the older drifts, a pronounced tendency to strong topographic expression in the form of kames, eskers, drumlins and terminal moraines. These features, taken along with the association with the ground-moraine of abundant water-sorted materials, and its comparative freshness and freedom from denudation, have permitted a fairly confident correlation of the drifts of this stage throughout the greater part of the continent. Whether this correlation will survive in the light of further research remains to be seen, but in the meantime it is of value as giving emphasis to the remarkable fact that there have been two types of glaciation in America, and of these the Wisconsin type is everywhere the later, and its outer limit is marked by the great terminal moraine of the American continent. Outside this moraine stretch the denuded but otherwise comparatively featureless sheets of till formed by the earlier glaciations. Inside are drifts showing not only a comparative freshness and freedom from denudation, but also a distinctiveness of character which indicates a marked difference in their mode of origin.

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[1] F. Leverett, "Comparison of North American and European Glacial Deposits," *Zeitschrift für Gletscherkunde*, Bd. iv. pp. 280 and 323 (1910).

Within the terminal moraine of the Wisconsin Ice-sheet are other belts of end-moraine marking stages in the retreat of the ice. The earlier of these are rudely concentric with the outermost moraine-belt, but at a certain stage there took place a marked alteration in the form of the ice-lobes, accompanied by at any rate local advance. This change in the form of the ice-margin separates what is known as the Later from the Earlier Wisconsin Stage.[1] It is accompanied also by a still further increase in the development of end-moraines, boulder-belts, kames, eskers, drumlins, outwash aprons, valley trains, and other glacial and fluvio-glacial features.

The Peorian stage.

The name Peorian has been applied by Leverett to denote the interval between the deposition of the loess and the Early Wisconsin till-sheet, which is seen at its margin, in numerous exposures and over a large area, to be superposed on the loess. Near the city of Peoria in northern Tazewell County, Illinois, a soil of this age is well exposed. The Shelbyville or Early Wisconsin till-sheet is here underlain by “ a bed of fossiliferous loess similar to that found on the surface of the Illinoian outside the limits of the Shelbyville drift-sheet, both in texture and age.” The upper part of the loess, which is altogether 8 to 12 feet in thickness, shows marked weathering, being of a reddish-brown colour to a depth of 3 feet, and thoroughly leached to a depth of 6 feet. Beneath this depth it is often calcareous, and the Shelbyville till immediately above the loess is also very calcareous. Although no actual Peorian deposits are present in these exposures, yet a considerable interval of time is probably represented by the weathered zone, and on account of the certainty with which both the loess and the Early Wisconsin drift can be identified, the district has been taken as a type and the time interval named after it.

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[1] The Shelbyville till-sheet belongs to the Early Wisconsin, the Bloomington to the later.

Having regard, however, to the doubt which exists as to the exactness of the correlation of the loess with the Iowan glaciation, the assumption that the interval thus defined as Peorian is co-extensive with an interglacial period is extremely unfortunate, and leads to much confusion. The same remarks apply to this as to the term Sangamon which we have previously considered. It is well, therefore, to restrict the use of these terms to the actual sense in which they have been defined by their author, understanding by the Sangamon Stage the interval between the deposition of the Illinoian drift and that of the overlying loess, and by the Peorian the interval between the Wisconsin and the underlying loess.

The sub-Wisconsin interglacial deposits.

Discussion as to the occurrence of an interglacial period between the Wisconsin and older glaciations does not, however, admit of much precision, and although the accurate defining of the term Peorian is desirable it is unessential to the argument. It is a well-established fact that extensive and wide-spread beds of peat and other fossiliferous deposits have been found intercalated between the Wisconsin till and an underlying sheet or sheets of till, the identification of which is in most cases very doubtful. This doubt, however, is a matter of minor importance, the essential point being that such beds do occur at the base of the Wisconsin drift, and that they overlie older drift-sheets. They are well developed in northern Illinois, notably in M'Henry, Kane, De Kalb, La Salle, and Bureau counties, the underlying drift here being probably in some cases Iowan. In central and western Illinois the intercalated deposits include the loess, which is then generally separated from the overlying Wisconsin drift by a soil and weathered zone (Peorian). In eastern Illinois the soils also occur beneath the Wisconsin and overlying a till-sheet which may be of Iowan age.

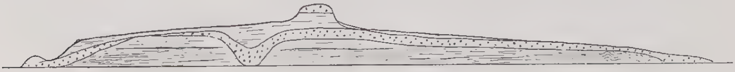

FIG. 52.—Diagram of section, 9½ miles long and 300 feet high, at Scarboro' Heights on the shores of Lake Ontario, near Toronto, showing the interglacial deposits. The boulder-clay is shown by dots, the middle glacial sands and the interglacial deposits by shading. Vertical exaggeration ten times. (After Coleman.)

The interglacial beds of Toronto.

But by far the most famous of all the American interglacial deposits is the *Toronto Formation* described by Coleman,[1] and exposed along the shores of Lake Ontario and in the Don Valley near Toronto. The section reproduced in Fig. 52, is that at Scarboro' Heights on the shores of the lake. It shows the typical threefold glacial series to a thickness of 180 feet overlying some 200 feet of fossiliferous silts, at the base of which boulder-clay has been proved. The section in descending order shows :

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[1] A. P. Coleman, "Glacial and Interglacial Beds near Toronto," *Journal of Geology*, iii. p. 322 (1895), and ix. p. 285 (1901).

5. Upper boulder-clay, yellowish brown, sandy, and weathered (englacial drift).
4. Middle glacial sands and gravels showing contemporaneous contortion (subglacial sands).
3. Lower boulder-clay, a stiff, blue calcareous till (ground-moraine).
2. The fossiliferous silts (interglacial).
1. The older boulder-clay underlying the silts (proved but not shown).

The hollow in the fossiliferous beds filled with boulder-clay is supposed by Coleman to be a pre-existing valley, and not to have been eroded by the ice. The beds are quite uncontorted close up to their contact with the boulder-clay, and this he thinks could hardly have happened if the ice had ploughed out the hollow, but is quite easily explainable if it merely filled up a pre-existing valley with drift. If this conclusion be correct, the lake in which the fossiliferous silts were formed must have been drained and the beds exposed to denudation before the oncoming of the second ice-sheet.

The fauna and flora obtained from this section have on the whole a slightly more northern aspect than those now existing in Toronto, and indicate climatic conditions probably equivalent to that of Lake Superior or southern Labrador. The fossils of the beds exposed in the Don Valley point, on the other hand, to a climate as warm if not warmer than that of Toronto at the present day. In neither exposure do the beds contain erratics or show any contortion which would prove the presence of ice during their formation. They indicate quiet deposition in water, the surface of which lay at least 140 feet above Lake Ontario.

Opinion is by no means undivided as to the interglacial significance of these beds. It is generally admitted that they must have been formed during a temporary retreat of the ice from the immediate neighbourhood of the sections, but there is the usual disagreement as to the extent of the retreat. It is interesting to note that this is one of two sections which have given Mr. Lamplugh pause in his general condemnation of the interglacial hypothesis. In his address to the Geological Section of the British Association in 1906,[1] he says, after describing the section, over which he was conducted by Professor Coleman :—

> On this and other evidence it is clear that during the course of the Glacial Period the whole of the district was for a considerable time released from the ice-sheets which previously and afterwards covered it. Moreover, in the opinion of Professor Coleman, some of the plants and shells of the warm climate beds denote conditions which would be incompatible with the persistence of ice-sheets anywhere in Canada ; and if this be so, then we here have proof for at least one interglacial epoch. But I still permit myself to feel doubt regarding this last-mentioned deduction, as the shells and plants in question, which have their present habitat in the Middle United States, even yet endure winters of considerable severity ; and there are certain factors in the composition of the beds and their altitude above Lake Ontario that justify caution. It is, however, mainly from my knowledge of this "Toronto formation" and of the Kirmington section in England, presently to be discussed, that I still maintain an undecided attitude in respect to the Interglacial hypothesis in its simpler form.

To my mind these interglacial beds fall naturally into line with those described by Leverett as distributed over a large area beneath the Wisconsin drift in northern Illinois. Taken in conjunction with the undoubted duplication in the rise of lakes Bonneville and Lahontan (see Chap. IX.), and the peculiar time relations there established, they seem to me to point to the conclusion that America has suffered two distinct glaciations, the last of which was relatively recent and separated by a very long interval from that which preceded it.

Classification of the American drifts.

We thus have arrived at the classification of the American drifts, which is briefly summarised in the following table :—

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[1] G. W. Lamplugh, "On British Drifts and the Interglacial Problem," *Presidential Address to the British Association*, York, 1906.

Extra-morainic Drift (supposed earlier glaciation)	Kansan till-sheet.	
	. . . . . .	Yarmouth soils.
	Illinoian till-sheet.	
	. . . . . .	A few exposures of loess-like silt.
	Iowan till-sheet .	Loess.
	. . . . . .	Peats, soils and Toronto, formation.
Intra-morainic Drift (supposed later glaciation)	Early Wisconsin till.	
	. . . . . .	Change of form of ice-lobes.
	Later Wisconsin till.	

On the whole this classification may be taken as fairly well established. One or two points, perhaps, require qualification. We know that loess was being formed in the latter part of Iowan times. This the peculiar relation of overlap teaches us. We do not yet, however, know for certain whether its formation was going on throughout the whole period of existence of the Iowan Ice-sheet. Nor yet do we know whether any of it is pre-Iowan in age. If the loess-like silts described by Leverett as occurring beneath the Iowan drift are really loess, this would seem to be the case, but, as we have mentioned above, Leverett does not appear to correlate them with the loess. The non-acceptance of the Toronto as an interglacial period would not invalidate the classification. Whatever opinion may be held regarding it, it cannot be denied that the later or Wisconsin drift was deposited under essentially different conditions of retreat from the earlier sheets, and that it is distinctly later in age.

CHAPTER IX

QUATERNARY LAKES OF AMERICA

Oscillations of water level in enclosed continental basins—The Dead Sea—The Great Basin—The pre-Bonneville alluvial cones—The Bonneville, Provo, and Stansbury shore-lines—The oscillations of the lake surface—The point of overflow—The Bonneville shore-line not determined by the outlet—Rapid cutting down of the outlet—The Provo shore-line determined by the outlet—Abundance of tufa on Provo shore—The sediments of Lake Bonneville—The double rise—Comparative salinity of the water in the two periods of rise—Summary of conclusions regarding Lake Bonneville—Relative duration of the two periods of high water—Relative duration of the pre-Bonneville, inter-Bonneville, and post-Bonneville periods of low water—Lake Lahontan—Comparison with Lake Bonneville—The shore-lines of Lake Lahontan—The tufa deposits—Their relation to the shore-lines—The sediments—The history of the rise and fall of the lake surface—The complete desiccation in inter-Lahontan and post-Lahontan times—Extent of pre-Lahontan time—The rise of the lakes due to an interruption of the normal climatic conditions—Correlation with the Glacial Period—Bipartition.

Water level in enclosed basins.

In endeavouring to follow the climatic oscillations of which we have abundant evidence in the glacial deposits of the Quaternary Period, anything in the nature of an independent record is of primary importance. Much has been effected in this direction by tracing the changes in the distribution of plants and animals, and of these investigations some account will be given in subsequent chapters. Another and very striking class of evidence is that afforded by the oscillations of water level in enclosed continental basins. The lakes in the lower parts of these basins, possessing no overflow, have their levels determined by the balance between supply and evaporation, and must, therefore, as was first pointed out by Jamieson[1] in 1863, be extremely susceptible to climatic changes. Lartet,[2] in 1865, was the first to describe an actual case of this kind. He showed that, about the end of the Tertiary or the beginning of the Quaternary Period, the waters of the Dead Sea must have had a considerably greater extent than at present, because, both to the north and south of the present limits of the lake, enormous stretches of country are covered by its sediments. This he interpreted as an effect of the Glacial Period, the influence of which is shown by the moraines on Mount Lebanon to have extended into neighbouring regions. This correlation was an important step in advance, but since the time of Lartet little progress has been made towards elucidating the former history of the basins of interior drainage in the eastern hemisphere. It is to America that we must turn for detailed investigations of this kind.

The Dead Sea.

The area known as the Great Basin lies in the Western States between the Sierra Nevada and Wasatch Mountains. Owing to a combination of causes, geographical and meteorological, as yet imperfectly understood, it is a distinctly arid region, characterised by small rainfall and a high rate of evaporation. Many of the lower depressions are at the present day occupied by lakes of varying salinity, the level of which is determined by the balance between supply and evaporation. The occurrence of shore-lines on the mountain slopes high above the surfaces, and of sediments stretching far beyond the limits of these lakes, proves that they were formerly much more extensive, and the geological recency of this period of high water is clearly shown by the freshness of the records it has left behind it.

The Great Basin.

Former greater extent of the salt lakes.

In the northern part of the basin there came into existence two especially large bodies of water, to which the names Bonneville and Lahontan have been given.

Lakes Bonneville and Lahontan.

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[1] T. F. Jamieson, *Quart. Journ. Geol. Soc.* vol. xix. p. 258 (1863).

[2] L. Lartet, *Comptes rendus de l'Académie des Sciences*, Paris, vol. lx. p. 798 (1865).

Lake Bonneville occupied the north-eastern part of the Great Basin in the state of Utah, and Lake Lahontan

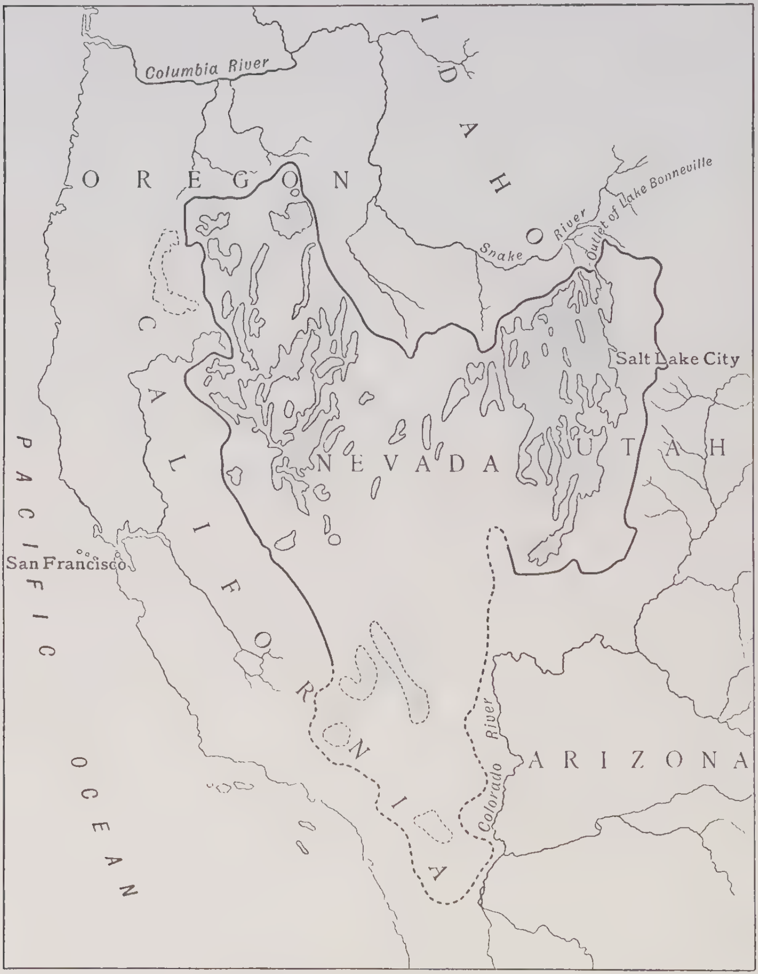

FIG. 53.—Map of the Great Basin, showing the position of Lakes Lahontan and Bonneville. The limits of the Basin are shown by the black line. (After Russell.)

the north-western part in Nevada. Several minor lakes accumulated in depressions in the southern half of the basin. Lake Bonneville has its modern representative in the Great Salt Lake, while the lower hollows in the Lahontan area are occupied at the present day by a few small brackish lakes.

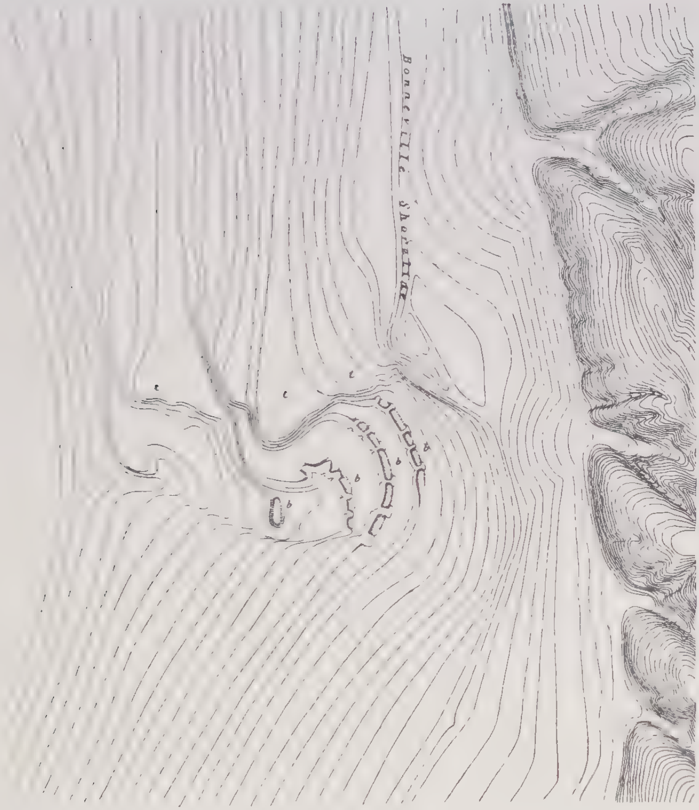

Fig. 54.—Contour map of the shore embankments of Lake Bonneville in Preuss Valley, Utah. (After Gilbert.)

The investigations of Gilbert[1] and Russell[2] into the history of these lakes have led to important results. They have shown that the epoch of high water was preceded by a prolonged period of aridity extending back into the past as far as a continuous record can be traced. They have proved also that the rise in both lakes was a double one, there being two periods of high water separated by a further period of aridity, during which the lakes were almost, if not completely, dried up. We will now give a summary of the evidence on which these conclusions are based, dealing first with Lake Bonneville and then with Lake Lahontan.

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[1] G. K. Gilbert, "Lake Bonneville," Monograph i., *United States Geological Survey*, 1890.

[2] I. C. Russell, "The Geological History of Lake Lahontan," Monograph xi., *United States Geological Survey*, 1885.

Lake Bonneville has left its record, in the form of wave-cut terraces, bars, deltas, and spits of shingle, on the slopes of the basin which it occupied. The only pre-Bonneville deposits are the alluvial cones. At the top these are separate, but lower down they adjoin, and their bases coalesce into a continuous scolloped slope, which can be traced beneath the cloak of sediment to the very bottom of the basin. Numerous shore-lines are observable on these cones and on the slopes of the mountains at all heights up to 1000 feet above Great Salt Lake. Three of these stand out pre-eminently, and two at any rate represent periods when the level of the lake was comparatively constant. These conspicuous shore-lines are known as—

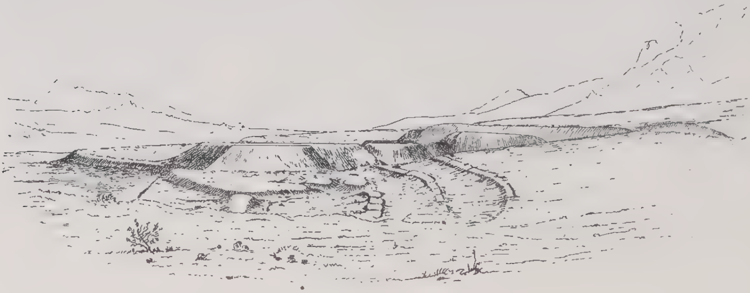

FIG. 55.—View of the embankments in Fig. 54, from the south.

The pre-Bonneville deposits and the Bonneville shore-lines.

The Bonneville Shore, 1000 feet above Great Salt Lake.
The Provo Shore, 625 feet above Great Salt Lake.
The Stansbury Shore, 330 feet above Great Salt Lake.

The deposits of the Bonneville shore-line are not of any very great magnitude, and are conspicuous mainly by their position at the top of the series. The absence of shore deposits at a higher level is explained by the fact that the lake found an outlet at a very short distance above this level.

All the evidence points to the Provo shore being more recent than the Bonneville. It is also much more pronounced. Its embankments are the most massive, and its wave-cut terraces the broadest of the whole series. The lake being smaller, and hence less suitable for the formation of large waves, we are forced to the conclusion that this was not due to more active erosion, but to the lake having stood for a longer time at this level.

The smooth sediment-covered slopes below the Provo shore exhibit a number of shore-lines. The strongest of these is the Stansbury. It represents a shorter period than the Provo, as is shown by comparison of the shore-lines formed by similar-sized sheets of water in the two stages.

Deposits of tufa are very abundant on the Provo shore, somewhat less so on the Stansbury.

Conclusions from the mutual relations of the deltas.

By the examination of the mutual relations of the deltas formed when the lake stood at the different levels, the following facts have been brought out clearly :—

(1) The Bonneville shore-line antedates the Provo.
(2) The Provo epoch was several times longer than the Bonneville.
(3) In falling from the Bonneville shore to the Provo the water lingered very little, if at all.
(4) In falling from the Provo level to the bottom of the basin the water occasionally lingered, but its lingerings were brief as compared to the halt at the Provo level.
(5) The water lingered during its advance antecedent to the Bonneville epoch, not standing long at one level, but oscillating up and down.

It would thus seem as if the water rose with oscillations to the Bonneville shore, a short distance above which it overflowed, and cutting an opening lowered itself rapidly to the Provo level. Here it remained for a relatively long period, and then subsided with minor oscillations to the Stansbury, where it received a slight check before continuing its recession to the present level.

The overflow.

Examination of the col through which the lake overflowed yielded some interesting evidence. It has been pointed out that the Bonneville shore-line is conspicuous mainly by reason of its position at the top of the series. It was not really determined by the level of the outlet, the carving of the shore being essentially completed before the discharge. As soon as that began the water level fell. At the Provo horizon, on the contrary, a constant or nearly constant water level was maintained by discharge for a very long time.

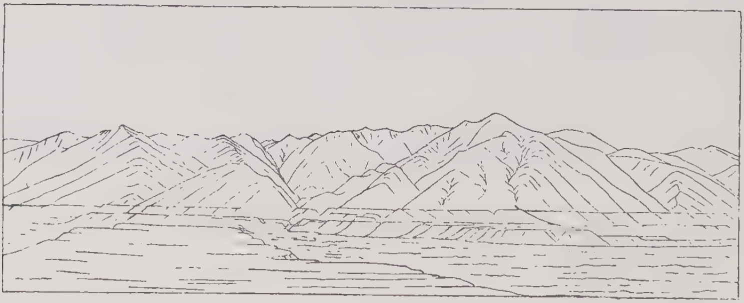

Fig. 56.—The deltas of the Logan River in Lake Bonneville as seen from the Temple. (After Gilbert.)

The point of discharge was Red Rock Pass at the north end of Cache Valley, and the escaping water descended into the valley of the Snake River. The outlet is several hundred feet deep and one-third of a mile wide. The pass was originally blocked by the alluvial cone of Marsh Creek and the profiles on either side of the outlet when produced meet above the level of the Bonneville shore. Owing to the softness of the alluvial material, the outlet, when once started, rapidly increased and the volume of water with it. Hence a cumulative effect and consequent *débâcle.* The outflowing stream is estimated to have rivalled even Niagara in its dimensions. How long it maintained its colossal size is not known, but the period cannot have been very great. The entire prism of water between the Bonneville and Provo planes would be discharged by Niagara in less than twenty-five years. The rocky bottom of the pass is fluted with erosion channels.

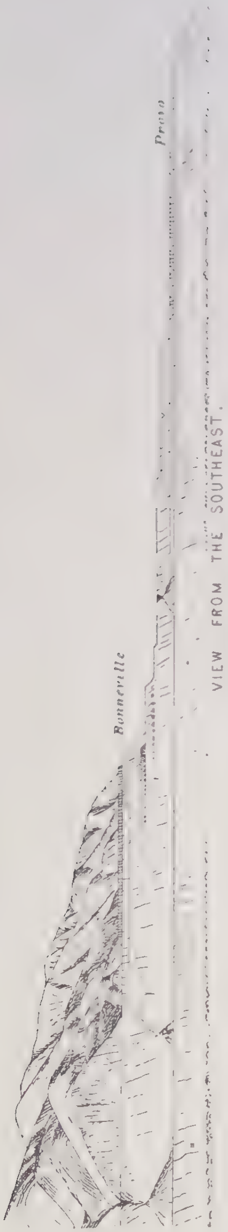

Fig. 57.—View of the shore terraces of Lake Bonneville, near Dove Creek, Utah. (After Gilbert.)

Explanation of the tufa on the Provo shore.

Cache Valley, from which the discharge took place, is separated from the Great Salt Lake basin by a range of mountains. At the Provo stage the only connexion between the sheets of water was the Gate of Bear River (see Fig. 58). At the Bonneville stage there were several straits. The Bear River, which now supplies half the water of the Great Salt Lake, flows into Cache Valley, which was a distributing reservoir for this supply during the Provo stage. The flow through the Gate of Bear River was not necessarily always in the same direction during the Provo period. Consequently, the fact of there having been an overflow in the Provo period does not of itself imply the absolute freshness of the lake. This may account for the abundance of tufa on the Provo shores. It has not been found on the Provo shore in Cache Valley.

To quote Gilbert, "It is certainly most remarkable that a concurrence of geographic and climatic conditions should enable a lake to maintain a higher degree of salinity than the water of the outlet limiting its size."

The lacustrine sediments.

Within the basin of Lake Bonneville, and strictly limited in its distribution by the Bonneville shore-line, is a series of lacustrine strata called by the surveyors the Bonneville beds. They cover nearly the entire surface of the basin, lying flat on the open plain, and gently sloping upwards at the bases of the mountains. As is to be expected, however, they only reach the upper limit of wave work in shallow bays and on gentle slopes.

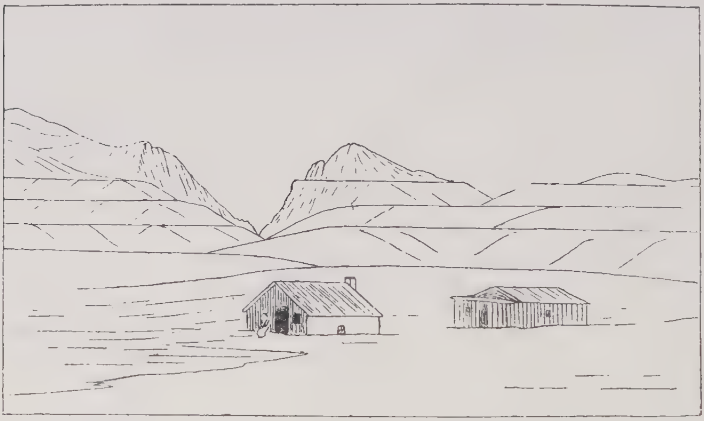

Fig. 58.—The Gate of Bear River from the east, showing the narrowness of the strait which connected Cache Bay with the main body of Lake Bonneville at the Provo Epoch. (After Gilbert.)

The beds rest in places on the principal mass of alluvium from the mountains, and support alluvium of recent transportation. This relation is strictly paralleled by the shore-lines, which rest upon the alluvial cones of the mountain bases and are themselves overlain by recent alluvium.

As a result of the deposition of the sediments, the base level of erosion of all streams flowing into the basin was raised, so as to make them agents of deposition along their lower courses in post-Bonneville time. Sections are therefore exceedingly rare. That representing the largest fraction of the Bonneville Period is exposed in the walls of the Old River Bed near the point where it is crossed by the overland stage-road. It exhibits the following members :—

3. About ten feet of fine sand passing down into
2. Ten feet of "White Marl" with some gypsum, and crowded at the base with shells representing nearly the same fauna as No. 1, which it overlies unconformably
1. Ninety feet of "Yellow Clay" laminated throughout with occasional local and discontinuous passages of sand. Gypsum and bivalve shells of several species.

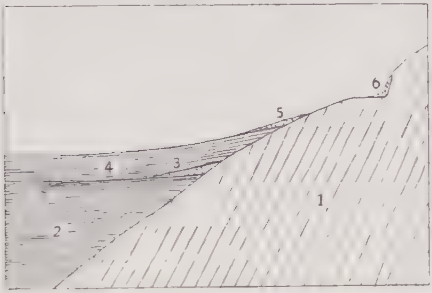

Fig. 59.—Section in the sediments of Lake Bonneville at Lemington, Utah.

(1) Palaeozoic sandstone. (2) The Yellow Clay (Lower Bonneville). (3) Wedge of alluvial gravel. (4) The White Marl (Upper Bonneville). (5) Recent alluvial gravel. (6) Bonneville shore-notch with recent talus.

The unconformity of the White Marl upon the Yellow Clay indicates discontinuity of lacustrine conditions, and at two localities this evidence is supplemented by the occurrence of subaërial deposits at the horizon of unconformity. One of these localities is at Lemington, where the Sevier River, issuing from its narrow valley in the Canyon Range, enters the Sevier Desert. Here is exposed the section shown in Fig. 59. The Yellow Clay and White Marl are here coarser in texture and

Subaërial deposits between the White Marl and Yellow Clay.

more sandy than usual, owing to their marginal position. Associated with them are two wedges of alluvium. The upper of these is a modern deposit. The lower, which is similar to the upper in all its characters, is inserted between the White Marl and the Yellow Clay.

The double rise of Lake Bonneville.

It is pretty obvious from these sections and others, that between the deposition of the Yellow Clay and White Marl the lake must have receded sufficiently to bring subaërial agencies into play. We have thus a period of low water separating two periods of high water.

Absence of overflow during the first rise.

That the first rise of the lake did not extend sufficiently far to produce overflow is proved by the absence of any sign of an older drainage channel than that at Red Rock Pass. If it had overflowed at this pass it could not have failed, owing to the softness of the alluvial material blocking the pass, to lower the outlet to the Provo level. This it certainly did not do, for during the second flood the water rose some 350 feet higher to the Bonneville Shore. The limits of the first rise are supposed to be indicated by some partly buried older embankments about 90 feet below the level of the Bonneville Shore.

Comparative salinity during the two periods.

The existence of remarkable differences in the constitution of the White Marl and Yellow Clay has led to speculation regarding the conditions of their accumulation. The White Marl in the centre of the basin contains a relatively large proportion of calcareous matter and of earthy carbonates which have been thrown down as chemical precipitates. It would seem as if the precipitation of sediment in the lake during the second period of high water was largely confined to the neighbourhood of the shores, and only went on feebly in the centre of the basin. The simplest and in fact the only plausible hypothesis that has been put forward to account for this difference between the two deposits ascribes it to comparative freshness of the water during the White Marl epoch. To test this several experiments were carried out by Gilbert and Russell. They took samples of water from three of the rivers tributary to the Great Salt Lake and of the brine of the Great Salt Lake itself. With each they shook up a certain amount of the Yellow Clay. It was found that the precipitation of the sediment took place rapidly in the water of two of the rivers, and was indefinitely delayed in the brine of Great Salt Lake. In the case of the third sample of fresh water, that of the Great Bear River, the results were discordant, for it was found that precipitation took place at equal rates in the water of the river, in the Great Salt Lake brine, and in all mixtures of the same.

On the whole, however, these experiments seemed to show that freshness of the water facilitated precipitation, while salinity retarded it. In the case of a comparatively fresh-water lake, sedimentation would go on actively round the margin of the lake, and would consequently be less copious in the middle. In the case of a more concentrated brine, the sedimentation being delayed would go on evenly all over the basin.

It would thus appear as if the more calcareous White Marl was deposited in comparatively fresh water, and, there having been no overflow during the first rise, this could only have been affected by the complete desiccation of the lake during the intervening period of drought and the covering up of the precipitated salts by alluvial deposits so as to prevent their re-solution. This process of freshening by desiccation has been observed by Russell to take place in some of the smaller existing lakes of the Great Basin.

Summary of conclusions.

We are now in a position to sum up the extent of our knowledge with regard to the history of Lake Bonneville. On reviewing the facts set forth in the foregoing pages it will be found that we have evidence of the following succession:—

(1) A long pre-Bonneville epoch of low water, represented by the alluvial cones of the mountain bases now buried in sediment.

(2) The first Bonneville epoch of high water, in which the

lake did not reach the rim of the basin and was not discharged. This period of high water is stratigraphically represented by the Yellow Clay and its upper limit is probably marked by some half-buried embankments about 90 feet below the Bonneville shore.

(3) The inter-Bonneville epoch of low water, in which there is some reason to suppose that the lake was nearly, or perhaps completely, desiccated. This period is represented by the unconformity between the Yellow Clay and White Marl, and by the alluvial wedges intercalated between these deposits.

(4) The second Bonneville epoch of high water, which culminated in overflow resulting in a rapid lowering of the lake to the Provo shore-line. This period is stratigraphically represented by the White Marl. The Bonneville shore-line records the surface at the date of initial outflow. The Provo shore-line records its position after the channel of outflow had attained its maximum depth. The lake remained at this level as long as the relations of the rainfall and evaporation enabled it to maintain an outflow. It then sank with oscillations to the bottom of the basin, experiencing on the way a temporary but decided check at the Stansbury shore-line. The problem of the Stansbury shore-line still remains unsolved, but the check was probably due to drainage into another basin in the Bonneville area where the water was evaporated.

(5) The post-Bonneville epoch of low water, extending to the present time. It is not improbable that complete desiccation was reached at some stage of this period.

Relative length of the Bonneville epochs of high water.

With regard to the absolute duration of the various periods nothing is known; we can, however, form some idea of their relative magnitude. From the much greater thickness of the Yellow Clay it would seem as if the first Bonneville epoch were considerably longer than the second. The whole thickness of the Yellow Clay is not known, but on the other hand the conditions during the first rise were probably much more favourable to the precipitation of mechanical sediment in the centre of the basin. Disregarding, therefore, the mechanical element in the sediments and considering only that due to chemical precipitation, we find that as far as it is exposed the Yellow Clay represents a period at least five times as long as that represented by the White Marl. The assumption of the constancy of the chemical precipitation of calcareous matter throughout the two periods is a very considerable one, and may be very far from the truth. On the whole, however, it seems as if there is very little doubt that the first rise occupied a considerably longer time than the second.

Relative length of the low-water periods.

We have no means of comparing the duration of the periods of low and high water, but a very good idea can be formed of the order of magnitude of the low-water periods. It is unquestionable that the pre-Bonneville epoch, represented by the great alluvial cones at the bases of the mountains, was out of all proportion longer than the inter-Bonneville and post-Bonneville epochs. A comparison of the few alluvial wedges referable to the inter-Bonneville epoch with their local representatives formed during the post-Bonneville epoch shows the former to be invariably the larger, and indicates that the time between the two Bonneville floods was longer than post-Bonneville time.

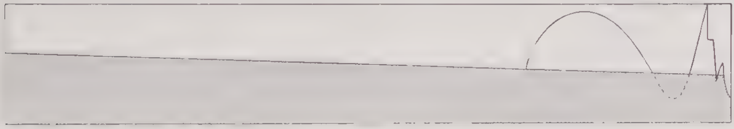

FIG. 60.—Diagram of the rise and fall of water in the Bonneville Basin. Horizontal distances from left to right represent time; vertical distances, height of the lake. The upper line of the figure is the horizon of the Bonneville shore. The shaded area represents ignorance. (After Gilbert.)

Lake Lahontan.

The Quaternary history of Lake Lahontan was in most respects similar to that of Lake Bonneville. Its rise was preceded, as in the case of Lake Bonneville, by a long period of arid climate. It had two epochs of high water separated by a period of desiccation. The second rise was, moreover, the greater, but unlike that of Lake Bonneville it did not culminate in overflow.

This difference is a most important one, for it gives to the Lahontan deposits a character of their own in many respects strikingly different from those of Lake Bonneville. The level of the lake, being at all times determined solely by the relation between precipitation and evaporation, was very inconstant, and hence none of the shore-lines attain the strength and grandeur of those Bonneville shores which were determined by the level of the outflow. This deficiency is, however, counterbalanced by the striking character and variety of the tufa deposits in the Lahontan basin, the study of which has confirmed and amplified the conclusions to be drawn from the lake sediments and abandoned shore-lines.

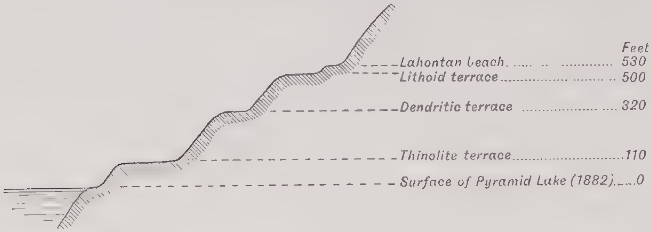

FIG. 61.—Generalised profile of the Lahontan shores. (After Russell.)

The shore-lines.

The highest or "Lahontan" shore-line is about 530 feet above the level of Pyramid Lake. Beneath it are three other conspicuous terraces, which have been named after the varieties of tufa of which they mark the upper limits. They are—

The Lithoid terrace, 500 feet above Pyramid Lake.
The Dendritic terrace, 320 ,, ,, ,,
The Thinolite terrace, 110 ,, ,, ,,

Their relations are shown in the above generalised profile of the Lahontan shores.

The Lahontan beach is a very inconspicuous feature compared with the three lower terraces. It is quite obvious that the lake lingered but a short while at its highest level. That it attained this level at some time subsequent to the cutting of the Lithoid terrace is shown by the fact that the Lahontan beach usually appears as a terrace of construction a few feet wide resting on the broad platform of the Lithoid terrace.

The tufa deposits and their relation to one another.

The three deposits of tufa, of which these terraces are the upper limits, are seen throughout the lower portion of the basin to be superposed on one another in the following order:—

3. Dendritic Tufa.
2. Thinolite Tufa.
1. Lithoid Tufa.

Their relations to one another, to the sides of the basin, and to the horizontal lake beds in its bottom, are shown in the following diagram:—

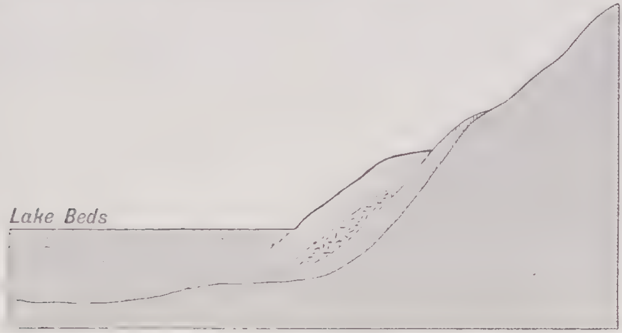

FIG. 62.—Diagram showing the succession of tufa deposits in Lake Lahontan and their relation to the lake beds. (After Russell.)

The first formed of these deposits, the lithoid tufa, is compact and stony in structure; the second takes the form of some unknown crystalline substance, after which it is in all probability a pseudomorph; while the third is arborescent in character. The tufa is found coating the rocks at the sides of the basin or rising into domes and towers of fantastic shape, which in section show the succession of the three forms.

The lacustrine sediments.

The sediments in the bottom of the Lahontan basin exhibit three definite divisions:—

Upper lacustral clays.
Medial gravels.
Lower lacustral clays.

The inter-Lahontan period of low water.

Wherever any considerable section of Lahontan sediments is exposed these three divisions appear in unvarying sequences. The middle series of current-bedded sands and gravels undoubtedly represents a low-water period, and it is a remarkable fact that it also occurs in places intercalated between the lithoid and thinolite tufas (see Fig. 65). Other evidence of a low-water stage between the deposition of these two tufa deposits is found in the weathering observed in places to have affected the lithoid tufa before the thinolite was deposited on top of it.

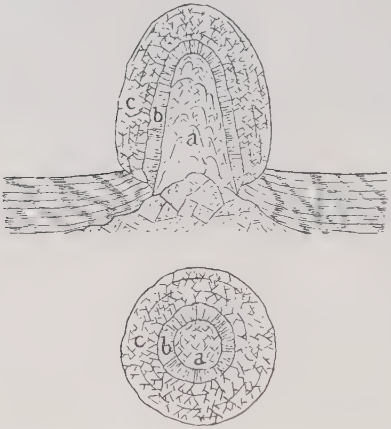

Fig. 63.—Vertical and horizontal sections of a tufa tower, Lake Lahontan.
a. Lithoid tufa. *b*. Thinolite. *c*. Dendritic tufa.

We thus have in the sediments evidence of two periods of high water, represented by the lower and upper lacustrine clays, separated by a period of low water represented by the medial gravels. We know also that the lithoid tufa was deposited during the first period of high water and the thinolite during the second. The dendritic tufa was formed during the same rise as the thinolite, for there is no evidence of discontinuity of deposition at their junction, but rather of a passage from one to the other represented by alternating thin layers of the two deposits.

Order and magnitude of the oscillations.

The connexion of the tufa deposits with the various terraces enables us to go further and define the extent of the two elevations of the water surface. The first rise extended (see Fig. 67) to the height of 500 feet above the surface of Pyramid Lake, where the water surface lingered sufficiently long to cut the broad Lithoid terrace. That it did not extend higher is shown by the absence of lithoid tufa above this level. It then

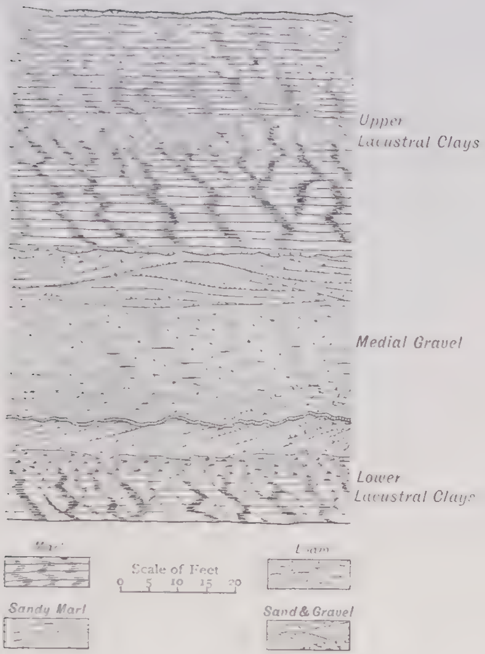

FIG. 64.—Section of the Lahontan sediments in Humboldt Cañon, Nevada. (After Russell.)

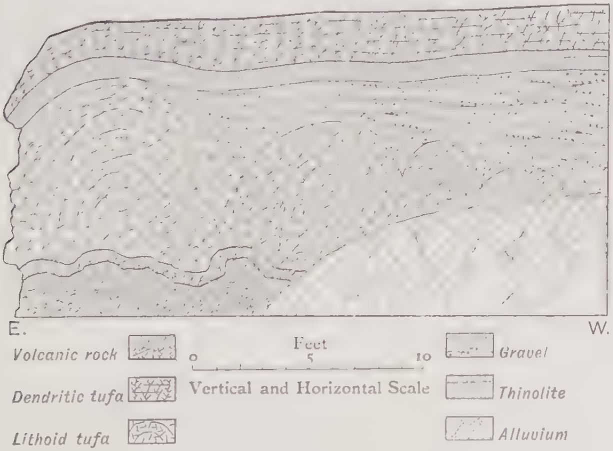

FIG. 65.—Section showing current bedded gravels between lithoid and thinolite tufa. (After Russell.)

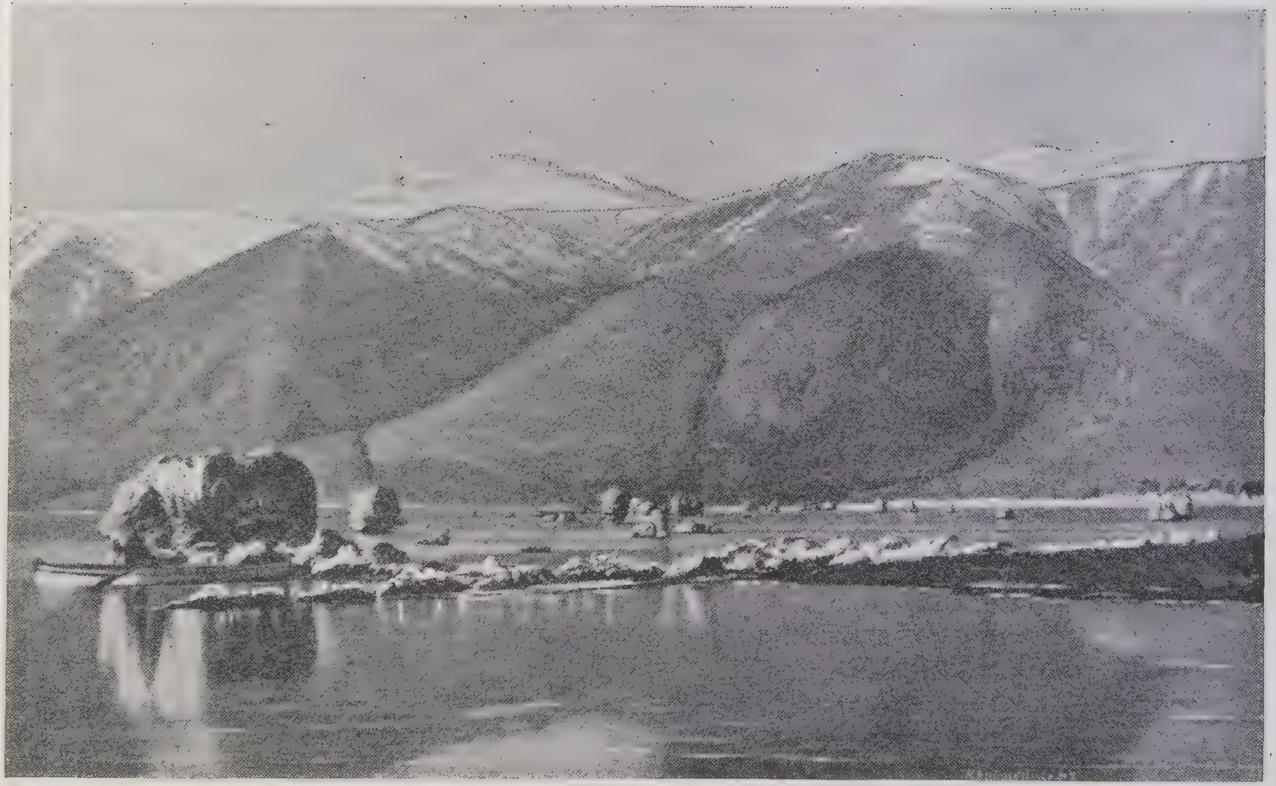

FIG. 66.—Tufa domes in Mono Lake, California. (After Russell.)

retreated, depositing on its way as a result of the concentration the lithoid tufa, and attained a sufficiently low level to permit of the deposition of the medial gravels and the weathering of the lithoid tufa. During its second rise it deposited thinolite until it attained a height of 110 feet. Here its advance received a check indicated by the Thinolite terrace. By the time conditions had again become favourable for the rise of the water-surface the brine had become altered, perhaps merely by dilution, but at any rate in such a way that it no longer deposited its calcium carbonate as thinolite but as dendritic tufa. This it continued to do until it reached an altitude of 320 feet, where another check caused it to cut the Dendritic terrace. During its subsequent advance to the Lahontan shore-line at 530 feet the water did not deposit any tufa, the "brine" being probably too weak to do so. From the Lahontan shore-line the water fell to the present level or below it.

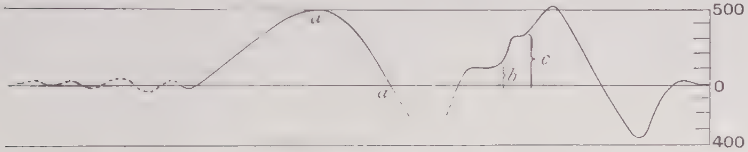

FIG. 67.—Curve exhibiting the rise and fall of Lake Lahontan. The figures indicate, in feet, the fluctuations of the ancient lake above and below the 1882 level of Pyramid Lake. (After Russell.)

aa. Deposition of lithoid tufa. *b.* Deposition of thinolite tufa. *c.* Deposition of dendritic tufa.

Freshening by desiccation in inter-Lahontan and post-Lahontan periods.

Only one point remains to be made, and that concerns the extent of the desiccation in inter-Lahontan and post-Lahontan time. The fact that the tufas deposited before and after the inter-Lahontan differ so much in character indicates a change in the composition of the brine, and the most probable cause of this change was partial or complete desiccation, causing certain salts to be deposited and covered up by sediments, so that their re-solution became impossible. Similar freshening by desiccation almost certainly took place in post-

Lahontan time, for the existing lakes of the basin only contain a feebly concentrated brine.

Similarity of the Bonneville and Lahontan records.

The most striking point in connexion with the history of these two great lakes, Bonneville and Lahontan, is the similarity of the climatic records presented by them. In both instances the rise of the lake was preceded by an arid period of great length, the record of which is preserved in the immense alluvial cones which extend everywhere to the bottom of the basin. There is no indication that this period was broken by any rise of the waters previous to that of the Bonneville-Lahontan epoch. The possibility that there may exist such records so old as to be buried within the alluvial cones is, however, not excluded; but it is at any rate clear that if such a previous rise did take place it did not culminate in overflow in the Bonneville basin. If it had it would have removed the loose alluvial material at Marsh Creek, and reduced the rim of the basin to the Provo level at this point. The restoration of these alluvial cones would imply a very considerable lapse of time.

In comparison with this pre-Bonneville period the comparative brevity of post-Bonneville time is very marked. Except locally, the embankments and shorelines show little trace of denudation, and are almost as fresh to-day as when they were made. Russell says of the Lahontan terraces, which are carved on the slopes of the ancient alluvial cones, that they "are but delicate inscriptions which, in a geological sense, are extremely ephemeral, yet they are clearly legible at the present day, thus indicating the recency of their origin." The post-Bonneville alluvial cones are, moreover, of diminutive size in comparison with those of pre-Bonneville age. They represent, however, a return to the extreme aridity which appears to be the normal climatic condition of the Great Basin. The Bonneville and Lahontan oscillations were interruptions, in the latest geological times, of this normal climatic condition, which otherwise seems to have extended with unbroken continuity far into the past.

Correlation with the Glacial Epoch.

This fact alone affords a great presumption in favour of correlation with the Glacial Epoch, for the latter is no less a departure from the normal sequence of climatic evolution exhibited by the gradual faunal changes in the Pliocene. The general lowering of temperature which accompanied the Glacial Period is, moreover, well known to have affected the mountain ranges of the Great Basin, and produced in them an enormous development of snow-fields and glaciers. All the higher portions of the Sierra Nevada to the west of the basin of Lake Lahontan were buried beneath a vast accumulation of snow and ice. Glaciers also occupied the valleys of the East Humboldt Range to the east, and traces of glaciation are also reported from some of the ranges in the centre of the basin. None of these glaciers, however, descended to a low enough level to reach the shores of Lake Lahontan. At the western base of the Wasatch Mountains in the Bonneville basin Gilbert found moraines which descended below the level of the Bonneville shore-line, but was unable to determine clearly their relation to the lake terraces. Much better evidence has been forthcoming in the case of the Mono basin, which was invaded by great glaciers which descended from the High Sierra on its western border. This basin was in Quaternary times occupied by a lake which attained a depth of nearly 900 feet, and the terraces of this lake can be distinctly traced not only on the moraines but also in the bed of the glacier behind. This relation shows that the retreat of the glaciers took place before the fall of the lake surface, but it does not in any way disprove the idea that the lake and the glaciers were in the main contemporaneous. It is easy to understand that the rise in temperature, which brought the glacial period to an end, would produce melting and diminution in the snow-fields long before it seriously affected the rate of evaporation in the lakes. Moreover, the melting of the snow and ice would bring an increased supply of water to the rivers and aid in maintaining or raising the lake surface.

Evidence of bipartition.

We may then regard the rise of the lakes with a fair amount of safety as the direct result of the climatic changes of the Ice Age. This leads us to consider the meaning of the double rise. In the Bonneville basin the evidence for this is based on a small number of sections, and might justifiably be challenged if it stood alone. In the case of Lake Lahontan, however, the matter stands on firmer ground. Here there are numerous sections showing the occurrence of alluvial gravels between the upper and lower lacustral clays and also between the lithoid and thinolite tufas. The lower clays were greatly denuded before the deposition of the upper clays, and the lithoid tufa was weathered before the deposition on it of the thinolite tufa. The concurrence of these various lines of evidence is irresistible, and it may safely be taken as established that the lakes of the Great Basin had two periods of high water separated by a prolonged arid period in which complete desiccation probably occurred. This is one of the strongest arguments that has been adduced to prove the bipartition of the American glaciation.

CHAPTER X

THE LOESS

Origin of the loess—The aeolian theory—Physical characters—Mode of occurrence—Fossils—Wind-borne and water-borne deposits contrasted—Conditions necessary for the formation of the loess—Source of the material—Marginal deposits—Salt-steppes and grass-steppes—Former wider prevalence of steppe conditions—Relation of the European loess to the glacial deposits—Connexion with the glacial outwash gravels—The Quaternary steppe fauna of Central Europe—Succession of tundra, steppe, and forest faunas—Interglacial deposits of Moscow—Relation of the loess to the glacial periods of the Alps—Loess-formation the concomitant of oncoming glaciation—Newer and older loess—The loess of America—The paha-ridges—Distribution of the American loess—The molluscan fauna—Relation to the glacial drifts—The pre-Illinoian loess—The belts of high atmospheric pressure—Occurrence of deserts, steppes, and Quaternary loess-areas within these belts.

THERE are few deposits of any age the characters of which proclaim its nature and origin more clearly than those of the loess. In structure, composition, distribution, and fossil contents it exhibits all the characters of a subaërial wind-borne deposit. As such it requires a climate where extensive dust formation by natural means is not only possible, but a thing of everyday occurrence; in fact, such a climate as exists at the present day in the steppes of Southern Russia and Siberia, where the surface is continually being buried by new layers of wind-borne dust entrapped by the scanty vegetation which clothes it.

Richthofen's theory.

In view of the clearness of the evidence, and the convincing manner in which it has been marshalled by Richthofen, the originator of the aeolian theory of the loess, it is strange with what slowness this fundamental idea has crept into geological science. It is now thirty-five years since Richthofen first put forward this theory in his classical work on China, and even at the present day we are hardly clear of discussions as to the nature of the seas and lakes in which the loess was supposed to have been deposited. This impermeability to new ideas, which is perhaps more characteristic of geologists than of the devotees of any other branch of science, is in this case the more remarkable, since the theory, when first put forward, was no mere suggestion, but was supported by a mass of evidence as convincing as any which has ever been brought to bear on an entirely new idea. Richthofen's experience of the development of the loess in China, the Mongolian Steppes, Thibet, the region of Khotan and Yarkand, and the south-western part of Asia, as well as in Europe, in districts where it is still forming at the present day, and where it has long since ceased to form, gave him a grasp of the subject which has never before or since been attained, and entitled him to speak with an authority which can hardly be overestimated. We can therefore hardly do better than follow his development of the subject, taking as our authority a paper communicated by him to the *Geological Magazine* in the year 1882,[1] shortly after the publication of his great work on China.

Characters of the loess.

The loess in its typical form is a fine-grained deposit, consisting of minute particles of hydrated silicate of alumina, quartz, felspar, mica, and other minerals, more or less cemented with carbonate of lime, the segregation of which gives rise to the well-known concretions called in German *Loesspüppchen*. It is also often impregnated with alkaline salts, and nearly always stained yellow with some ferruginous matter. In homogeneity of composition and structure it presents a remarkable contrast to all sediments known to have been deposited by water, which, with the possible exception of those

Homogeneity and absence of stratification.

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[1] F. Richthofen, "On the Mode of Origin of the Loess," *Geol. Mag.*, 1882, p. 293.

formed in the oceanic depths, show considerable vertical and lateral variations. There is, moreover, in the loess an almost complete absence of any stratification, and the particles of mica are uniformly distributed without orientation. In a water-borne sediment the micas are, on the contrary, always arranged horizontally, and owing to the slowness with which they settle are often collected together in separate layers.

Vertical cleavage.

A striking character of the loess is its tendency to cleave vertically. This is almost entirely due to its being permeated by innumerable tubes, more or less vertical, generally encrusted with carbonate of lime, and ramifying downwards like the roots of grass. Where the surface is covered by vegetation the tubes are occupied by rootlets to a depth of several feet from the surface. This tendency to vertical cleavage results in the formation of perpendicular bluffs along the margins of hollows of erosion.

Mode of occurrence.

In its distribution the loess is independent of altitude. In China it ranges from a few feet to 8000 feet above sea-level, and in Europe it occurs at all elevations up to 5000 feet. In hilly regions it occupies the depressions between the ridges, the surface rising on all sides towards the hill-slopes. The line of profile of the surface resembles the form that would be assumed by a rope stretched loosely from hill to hill. Where the thickness of the deposit is considerable, as in the great inland basins and salt-steppes of Central Asia, the minor irregularities are submerged and the loess sweeps from range to range in an unbroken sheet. At the margins adjoining the hill-slopes intercalations of scree material can often be seen interbedded with the loess. Layers of angular fragments extend out from the slope, beginning with a slight inclination and finally passing at some distance into a horizontal position. Such deposits are, however, completely absent in the centre of the larger basins, where the loess becomes, from top to bottom, absolutely homogeneous.

Fossils.

The fossils of the loess consist almost entirely of land animals. Snail-shells are found embedded in it in immense numbers, and even the most delicate of these are perfectly preserved. They are distributed evenly throughout its mass, and not accumulated in layers, as they would be if deposited by water. Fresh-water shells are of extremely rare occurrence. Great numbers of bones of mammals occur locally. These mostly belong to forms which abound on steppes and grassy plains, but in the Quaternary loess there are also some extinct forms.

Deposits of aeolian and aqueous origin contrasted.

Now these properties which have just been enumerated are exactly those which might on *a priori* grounds be expected in a subaërial wind-borne deposit, and do not resemble in the slightest degree the properties of aqueous deposits. The latter are for the most part stratified and lacking in homogeneity, and as regards their vertical distribution have in general a definite upper limit determined by the surface of the water. Instead of intercalated screes they exhibit at their margins shore deposits, and their included fossils are not generally land-mammals and land-shells.

A wind-borne deposit on the other hand is homogeneous, and uniformly fine grained because of the minuteness of the particles which the air is capable of transporting to any distance. Such a deposit is also unstratified on account of the rapidity of its deposition from the extremely light medium in which it is suspended, and because the growth of vegetation on the surface is inimical to the production and preservation of planes of bedding. Its vertical distribution need be limited only by the thickness of the atmosphere; it would naturally contain scree deposits at the margins; and finally, no fossils are more likely to be entombed in it than land-shells and land-mammals.

Essential climatic conditions.

In regions where the rains are equally distributed throughout the year little dust is formed, and the consequent growth of the vegetation-covered soil is exceedingly small; but where a dry season alternates with a rainy season the amount of dust which is put in motion and distributed through atmospheric agency can reach enormous proportions. In Central Asia and Northern China dust storms at times conceal the sun for days in succession. A fine yellow sediment of measurable thickness is found deposited after every storm over large extents of country. Where this dust falls on barren ground it is very often carried away by the next wind, but where it falls on vegetation its migration is stopped, and in time immense accumulations may result.

Origin of the material.

The origin of the material which goes to form the loess is not far to seek. All the agents of denudation which lend a hand in the formation of aqueous sediments are effective also in supplying material to be distributed by the winds. Most important in this respect are no doubt the rivers, which, emerging from mountain regions, discharge their burden of debris and sediment on to the plains. Pavlow[1] points out how under certain conditions of climate and at the margin of steppes the action of torrential rains becomes of primary importance. In the plain which slopes away from the mountains of Kopal Dag in Turkestan, the torrents during heavy rains spread out on the plains large sheets of water which soon disappear by evaporation and infiltration in the soil. The debris swept out of the little mountain valleys is distributed widespread on the plains, the finer sediment being carried as far as the sheets of water extend. The sections in the plain in this district show a progressive increase in the coarseness of the sediment as one approaches the mountains, and beds of angular debris, due to excessive floods, are frequently intercalated in the deposit. To what extent this flood material is worked over by the wind and transported farther afield is entirely a question of local conditions, such as the scantiness of vegetation, the intervals at which the floods succeed one another, and so on. Towards the margins of steppes there is thus a certain amount of aqueous sediment interbedded with the loess proper,

Marginal conditions.

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[1] A. P. Pavlow, "Sur le loess de Turkestan et de l'Europe," *Geologisches Centralblatt*, Bd. vi. No. 1, p. 11 (1905).

but far out in the centre of the great basins almost the whole of the material is wind-borne.

Much of the dust deposited on the steppes of Asia is derived from the practically rainless deserts of the interior. In these deserts there is an incessant comminution of material due to insolation, and the action of sandblast on the rocks, and an equally incessant removal of every fine-grained particle, which is transported by the wind to adjoining less arid regions, where the anchoring effect of vegetation brings it to rest.

In addition to these two main sources of material, torrent and desert denudation, there are numerous other minor or accidental agencies which provide material for distribution by the wind. The sediments of desiccated lakes, the sands and muds left bare by the retiring of the sea, and the flood loams of rivers, especially those which come heavily charged with sediment from glaciated regions, may all be laid under contribution for the building up of the immense sheets of loess which clothe the semi-arid regions of the earth.

No doubt a certain amount of the dust which is formed in these regions finds its way into river, lake, or sea, and is deposited as sediment in water. A large proportion, however, inevitably comes to rest on the land, to be swept away again by the next wind, or covered up by another layer. Where the covering of vegetation is nicely adjusted there will be much deposition and little removal, and in such situations an incessant growth of the soil may go on for thousands of years. Endless records of the past, even the ruins of buildings and cities, may thus become covered up in dust, and at times so gradually that the roots of the grass of to-day may penetrate the land surface of a century ago.

Salt-steppes and grass-steppes.

Richthofen has called attention to the fact that there is a very essential distinction between the salt-steppes of the centres of the great continents and the more widely distributed grass-steppes. The former are always enclosed basins without drainage to the sea. Wind-borne deposits may be laid down in such an area even without the anchoring effect of surface vegetation, the growth of which is hindered by the salt which accumulates owing to the absence of exterior drainage. The grass-steppe, on the other hand, need by no means be an inland basin, although certain portions of these basins may have this character, and there of course exist a series of gradations between it and the salt-steppe. Under this head are to be classed the great grass-covered plains known in different parts of the world as prairies, savannas, llanos, pampas, and steppes. These all lie in regions characterised by the prevalence of a dry season during some part of the year. They are distinguished from the drainless salt-steppe by their level surfaces, and by the fact that they are crossed and partly drained by large rivers, the catchment areas of which lie entirely beyond their boundaries. Some of these regions are very moist in the wet season, and bear a luxuriant vegetation of grass and flowering herbs, but suffer greatly from drought during the rest of the year. The material deposited on their surfaces is for the most part derived from adjoining regions.

Former wider prevalence of steppe conditions.

The parts of Asia characterised by the prevalence of steppe conditions were in former times much more extensive than they are at the present day. The deep trenching of the rivers and streams over large areas of loess-covered country in China demonstrates a marked change of climate. More copious precipitation is now eating away the loess in the regions where it was formerly deposited in enormous thicknesses. The contrast between the present conditions and those which prevailed in Northern China during the loess period is much the same as that between this region and the steppes of Mongolia at the present day. As Richthofen says, "an eye-witness of this geological revolution would see no more than comes at the present day under the observation of the traveller as he descends from the Mongolian salt-steppes, with their uniform vegetation, their animals peculiarly adapted to a roving kind of life, and their nomadic and unagricultural people to the loess basins of China, the characteristic feature of which consists in the labyrinthic ramification of very narrow gulches cut in the yellow soil to a very great depth and with perfectly vertical faces."

In Europe, as in China, the districts now covered by loess were in former times steppes, having a marked continental climate with arid seasons. As in China also, the loess of Europe can be traced from regions where it is no longer being formed to where it is in process of formation under steppe conditions in the south-east of Russia. The loess extends in a broad belt from France and Belgium through Middle Germany, occurring in the Harz, Thüringerwald, Erzgebirge, and Riesengebirge, and eastwards to the northern slopes of the Carpathians, where it verges into the big loess plain of Podolia. In the loess of the Europe-Asian continent, we are but dealing with the evidences of a former wider distribution of the conditions which characterise a great part of the more central portions of this continent at the present day.

Relation to the glacial deposits of Europe.

In one respect, however, the loess of Europe surpasses in interest that of China, namely, that we can see here the relation to the glacial deposits, a relation which will be found to be of more importance in determining the nature of the cause of the Ice Age than any other fact that has been established with regard to it. The investigations of Penck and others have revealed the fact that the loess occurs thickly all along the border of the glaciated districts on the continent of Europe. This glaciated district shows an outer belt characterised by an absence of morainic topography, and an inner area where such topography is strikingly developed. The outer belt has a distinct maturity of drainage, and exhibits the marks of extensive denudation. The drainage of the inner area has every sign of youth, and has apparently suffered little denudation. The outer belt is covered with loess. The inner area is absolutely free from it. The conclusion is obvious, that the deposition of the last formed part of the European loess took place later than the maximum extension of the ice, but ceased before its complete withdrawal.

Let us now examine more closely this exceedingly important relation. We are indebted to Penck for a very complete discussion of the subject in his paper on the relations of man to the Ice Age.[1] He points out that there is an undeniable connexion between the horizontal distribution of the outwash gravels of the old ice-sheets and the loess. Districts in which these Quaternary river gravels prevail are, in middle Europe, marked loess areas. The loess follows the valleys along which these old fluvio-glacial gravels extend, and occurs thickest on the surface of the gravels themselves. Along with the gravels it increases in thickness towards the margin of the actually glaciated district. Such a genetic connexion suggests at once a common origin for both deposits, and seems to indicate that the loess is simply the flood loam of the rivers which laid down the fluvio-glacial gravels.

Connexion between the glacial outwash gravels and the loess.

The vertical distribution of the loess, however, separates it off at once from the Quaternary gravels, and shows how untenable such a simple hypothesis is. The Quaternary gravels lie at an altitude above the present river strictly limited by the former level of the latter. The loess knows no such bounds. It rises considerably higher than the gravels, and even spreads itself in the form of a sheet from one valley into another. For example, near Passau on the Danube the Quaternary outwash gravel from the glaciers of the Alps only rises 10 or 20 metres, while the loess extends to 100 or 150 metres above the river. Again, near Mainz on the Rhine the loess reaches double the height of the Quaternary gravel, and so frequently is this repeated that it becomes quite apparent that there exists no connexion whatsoever between the vertical distribution of the loess and that of the old river gravel. The height of water which served for the accumulation of the latter is quite insufficient for the deposition of the loess, which lies high above any undoubted former level of the river, and often, indeed, high above any possible level which it could attain under present geographical conditions. Thus the fluviatile hypothesis of the origin of the loess is quite insufficient to explain its vertical range, which indeed is not reconcilable with any other agency than that of the wind.

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[1] Albrecht Penck, "Mensch und Eiszeit," *Archiv für Anthropologie*, Bd. xv., 1884.

Explanation of this connexion.

From this apparent dilemma we have been rescued by the suggestion of Penck that both fluviatile and aeolian agencies may have had a hand in the production of the European loess. If it is assumed that it was originally a river sediment we have an explanation of its distribution along the valleys, while a subsequent rearrangement by means of wind would account for the heights it reaches on the sides of the valleys and on the uplands between them.

Independent evidence of steppe conditions in the Quaternary Period.

This combination of two distinct agencies not only affords a complete explanation of the phenomena, but seems demanded by the nature of the case. Few will be inclined to deny the connexion with the rivers and the original sedimentary nature of the materials. That conditions suitable for the conversion of this material into dust existed during the formation of the loess we are, fortunately, able to establish quite independently. Herein lies the peculiar beauty of the researches of Nehring.[1] His investigations of the mammalian fauna of the loess, and his deductions therefrom as to the climatic conditions which led to its production, will always rank among the most remarkable advances in geology. His careful and detailed work in the quarries of Thiede and Westeregeln has proved that after the retreat of the ice the North German Plain was occupied first by a fauna similar to that of the tundras of Northern Europe and Asia, that this in turn was succeeded by a steppe or dry-climate fauna, this latter being the predominant fauna of the loess. Finally, this in turn was superseded and gave place to the forest fauna of the Neolithic epoch. An account of the various species comprising these faunas has been given in the chapter on Pleistocene mammals, and it will be only necessary here to draw further attention to the conditions under which the discoveries were made, and to emphasise the conclusions to be drawn from them.

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[1] Nehring, *Tundren und Steppen.*

The Quaternary steppe fauna of Central Europe.

In the Westeregeln quarry, in the years 1874, 1875, and 1876, Nehring found at a depth of 10 to 20 feet from the surface remains of rodents which now characterise the east Russian and west Siberian steppes. The most important among these were the jerboa (*Alactaga jaculus*) and the suslik (*Spermophilus rufescens*). There were found besides remains of the marmot (*Arctomys bobac*), an old and a young individual of the pika or tailless hare (*Lagomys pusillus*), and numerous field-mice (*Arvicola gregalis*, etc.), such as now live in the eastern steppe districts; also remains of the wild horse and of a young *Rhinoceros tichorhinus*.

These animals, which, with the exception of *Rhinoceros tichorhinus*, now extinct, may be all said to be more or less indicative of steppe conditions, have been found in numerous other localities in middle Europe. The most important of these discoveries, both for the determination of the geological age of this fauna and its relation to the better known arctic fauna of Pleistocene Europe, was that at Thiede. Here, in the famous Thiede quarry, Nehring found remains of the jerboa and spermophile. These lay in the loess-like deposits of the middle levels, that is, above those beds in which the remains of lemmings and other arctic animals especially occur. They must, therefore, be ascribed to a somewhat younger epoch. The general superposition of remains of the steppe animals, both at Westeregeln and Thiede, on those of the arctic or tundra animals is quite clear, yet there occur in both localities, on the level of or even above the jerboa remains, a few remains of lemming. It is possible, however, that during the steppe period conditions suitable to the lemming may still have existed in the mountain ranges, and the presence in the deposits of the plains of occasional lemming remains might be accounted for either by the autumnal migration or by transport by birds of prey.

In fact it is, according to Nehring, impossible to imagine the lemming and jerboa dwelling together in the same district except on the assumption of an enormous change in the manner of life of either species. The jerboa inhabits steppe districts with dry, loamy, sandy soil, in which it can construct its underground holes without fear of collapse or of flooding; it requires a dry, hot summer and a vegetation composed of bulbous and other steppe plants. It never occurs north of 55° N. latitude, and is completely absent in the tundras, in the frozen ground of which it could not exist. It is entirely otherwise with the lemming, which is quite at home in the tundras. Since it cannot disturb the damp frozen ground, it constructs no deep holes and undergoes no winter sleep.

It is equally impossible to imagine either the pika, the marmot, or the suslik living in the neighbourhood of the lemming. On the other hand, it is very probable that these steppe rodents were in many places the successors of the lemmings, and that at the foot of mountains there may have been in places a certain proximity of the districts which they inhabited, and where a slight intermingling of their remains might easily take place.

Supposed succession of tundra, steppe, and forest.

Nehring lays emphasis on the fact that during the maximum of the Ice Age the districts outside the borders of the ice-sheets must have been of the nature of tundras, and inhabited by a corresponding fauna and flora. As the ice retreated this fauna and flora took possession of the ground abandoned by the glaciers, and retreated to the north and to the mountains as the climate became less cold. The steppe fauna and flora then appears to have extended itself from the east and south-east, as the districts adjoining the eastern steppes became sufficiently dry to allow of the thriving in them of the steppe plants and animals. The forests, which were absolutely destroyed in those areas invaded by the ice, no doubt managed to drag on a limited existence in certain districts outside the glaciated area, and from these they extended again when conditions of climate permitted. In many places they may have immediately succeeded to the tundra vegetation, but other districts they were certainly unable to occupy till the passing away of steppe conditions.

This conception of the succession of tundra, steppe, and forest was all that seemed justified by the evidence as it presented itself to Nehring. In the light of recent researches, however, some doubt arises as to whether the relation has really been so simple. To this point we will return later. In the meantime we may regard it as an established fact that the North German Plain was occupied in succession by two faunas, distinct from one another and from that which exists in the region at the present day. The first, or "lemming" fauna, was identical with that which now inhabits the permanently frozen ground of the tundras of Northern Europe and Asia. The second, or "jerboa" fauna, is now confined to the steppes of Siberia, which are characterised by the dryness of their climate and by the fact that loess is actively forming on them at the present day. Since these animals have been found in the European loess, we can hardly doubt that the conditions under which it was formed were not essentially different from those of the Siberian steppes. It may, therefore, be regarded with confidence as a subaërial deposit, formed under dry conditions of climate, and distributed in large measure by the agency of wind.

Relation to glacial deposits.

We are now in a position to be able to appreciate the evidence as to the nature of the relation of the European loess to the Pleistocene glaciation. We have mentioned above that it overlies the outer or older drift-sheet, and is wanting on the inner or younger. Such a relation can only be said to prove rigidly that it was deposited after the older drift-sheet was uncovered by the ice and before the newer sheet was laid bare. It is, however, extremely suggestive of an interglacial age. If so, we might expect to find here and there beneath the later sheet remnants of loess extending, perhaps, as far north as the ice retreated during the interglacial period. Only one such occurrence is at present known. This was discovered in the province of Moscow, in Central Russia, and has been described by Bogolübow.[1] There are here two boulder-clays between which occur a series of interglacial deposits, the lower portion of which consists of lacustrine marls, and the upper of loess and loess-like loam. The lacustrine marls contain remains of spruce, larch, willow, and alder, and clearly indicate a forest phase with cold-temperate climate. To this succeeded a steppe phase which led to the deposition of the loess on top of the lacustrine beds. The glacial deposits of this region are as yet hardly well enough

Inter-glacial deposits of Moscow.

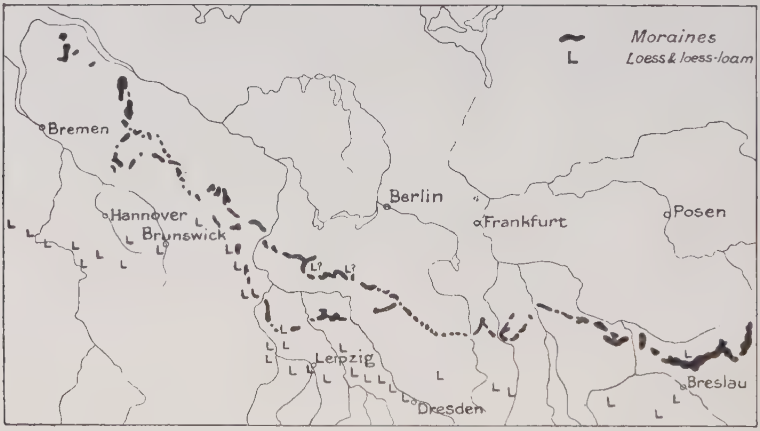

Fig. 68.—Map showing the relation of the most northerly occurrences of loess and loess-loam to the outermost young end-moraine in Germany. (After Werth.)

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[1] N. Bogolübow, "Über die Phasen der interglazialen Epoche im Gouvernement Moscau," *L'Annuaire géologique et minéralogique de la Russie*, vol. ix. p. 33 (1905).

known to determine how great a retreat was necessary, or to enable any correlation to be made with other districts.

Relation to the glacial periods of the Alps.

It is, however, on the margin of the alpine glaciation that we obtain the most important evidence on this point. It has been clearly shown, as we have pointed out in Chapter VII., that, associated with each of the four moraines referred by Penck to his four glacial periods, there occurs a great train of outwash gravel traceable for long distances outside the glaciated region, and known respectively as the Older Deckenschotter, the Younger Deckenschotter, the High Terrace Gravel, and the Low Terrace Gravel. Now loess has been found intercalated between the Younger Deckenschotter and the High Terrace Gravel, and between the High Terrace Gravel and the Low Terrace Gravel. The relation may be exhibited diagrammatically as follows:

Würm Glaciation	Lower Terrace Gravel
	Loess
Riss Glaciation	Upper Terrace Gravel
	Loess
Mindel Glaciation	Younger Deckenschotter
	?
Günz Glaciation	Older Deckenschotter

It is a not unnatural presumption that as it was formed in two of the three interglacial periods, it may also have been formed in the third, and that it will some day be proved to exist between the Younger and Older Deckenschotter. However this may be, the relations to the Würm Glaciation are at any rate in some respects very definitely known. No loess occurs on the Low Terrace Gravel, which is the outwash of the Würm glaciers, whereas it occurs thickly on the other three terraces. There does not, therefore, appear to have been any steppe period after the Würm Glaciation. More definite evidence still has been obtained in the district of the Salzach glacier, where loess-like loam has been found between the moraines of the Riss and Würm Glaciations, and near Bianne, east of Lyons, where actual fossil-bearing loess occurs beneath the moraine of the Würm Glaciation.[1] No loess lies anywhere on this moraine, whereas it occurs copiously on the Riss moraine. There is no escape, therefore, from the conclusion that a steppe period intervened between the Riss and Würm Glaciations, and that it did not overlast the maximum of the Würm Glaciation.

Fauna contrasted with that of the typical interglacial deposits.

If, however, the fauna of the loess be taken into consideration, it is found to be essentially different from that of the typical interglacial deposits such as the Schieferkohlen of Switzerland. The latter is a temperate wood fauna with the red deer, *Rhinoceros merckii*, and *Elephas antiquus*; the former a steppe fauna, including, instead of the above, the horse, the woolly rhinoceros (*Rhinoceros tichorhinus*), and the mammoth (*Elephas primigenius*). Now the woolly rhinoceros and the mammoth have with good reason come to be regarded as elements of the glacial fauna of Europe. The loess, which stratigraphically is interglacial, must therefore be regarded as connected either with the waning of the Riss Ice-sheet or the growth of the Würm Ice-sheet. Fortunately its archaeological contents leave no doubt to which of these two periods it is to be assigned. These are almost entirely Younger Palaeolithic (*Aurignacio-Solutréen*), and so closely allied to the Magdalénien industry of the Würm Ice Age as to make it inconceivable that they could be much older. Penck has, therefore, come to regard the loess as the concomitant of oncoming glaciation. According to his most recent conception, an interglacial period embraces three successive phases:

Loess-formation the concomitant of oncoming glaciation.

(1) A phase of erosion and deposition resulting in the silting up of the hollows produced in the preceding Ice Age. Flora, fauna, and climatic conditions as yet almost unknown.

(2) A phase of continued erosion and deposition with weathering. Forest conditions with temperate fauna, including red deer, *Rhinoceros merckii*, and *Elephas antiquus*.

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[1] Penck and Brückner, *Die Alpen im Eiszeitalter*, pp. 155, 644, and 1159.

Climate oceanic. Period of the Höttinger breccia, the Schieferkohlen, and the interglacial tufa deposits.

(3) A phase of loess-formation. Steppe conditions with colder fauna, including horse, *Rhinoceros tichorhinus*, and *Elephas primigenius*. Climate continental. Oncoming of the next glaciation.

Newer and older loess.

Now if, as the evidence round the Alps tends to show, there was a recurrence of steppe conditions towards the close of each interglacial epoch, we might reasonably expect to find loess of more than one age in the European plain. It has long been maintained by certain geologists that it is actually possible to distinguish an older and younger loess. No convincing evidence in this direction, however, was available until, in 1910, Schmidt and Wernert[1] showed that in the loess station of Achenheim, in Alsace, it was possible to effect the subdivision on archaeological grounds. They demonstrated here in superposition a Younger Loess of Young Palaeolithic (*Aurignacien*) Age, and an Older Loess of Old Palaeolithic (*Acheuléen*) Age (see Chap. XI.). The following is a schematic presentation of the section at Achenheim:

Humus.

Younger Loess.
(*l*) Loam-zone (Younger loess-loam).
(*k*) Younger Loess.
(*i*) Loam-zone ....Aurignacien.
(*h*) Younger Loess with arctic micro-fauna at base—main rodent bed in the Younger Loess.
←—Two implements suggestive of Moustérien industry.

Older Loess.
(*g*) Loam-zone (Older loess-loam).
(*f*) Older Loess......................Younger Acheuléen.
(*e*) Loam-zone ....Hearths.
(*d*) Older Loess
(*c*) Loam-zone } No archaeological remains as yet discovered.
(*b*) Older Loess
←—A hewn scraper.
(*a*) Diluvial sand.

In the bed (*f*) was found a *coup-de-poing* of local hornfels with only one side retouched. The curved reverse side only shows traces of working along one edge. Such one-sided *coups-de-poing* are rare in the Cheléen, but more frequent in the Younger Acheuléen. Like the Younger Acheuléen implements, it is made not from a complete boulder but from a bulb-splinter.

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[1] R. R. Schmidt and P. Wernert, "Die archäologischen Einschlüsse der Löss-Station Achenheim (Elsass) und die paläolithischen Kulturen des Reintallösses," *Prähistorische Zeitschrift*, Bd. ii. p. 339 (1910).

This section affords the first direct proof of the occurrence of a steppe phase in Older Palaeolithic time. It moreover further defines this phase as coincident with the Acheuléen, and it is of interest to note, in connexion with Penck's conception of the relation of the steppe phases to the glacial periods of the Alps, that the fauna of the Acheuléen is indicative of a transition to colder conditions (see Chap. XII. p. 270). On this latter ground it has been correlated by Penck with the oncoming of the Riss Ice Age, the maximum of which occurred during the earlier colder portion of the Moustérien (p. 290). There are, therefore, very strong grounds for believing that a genetic connexion exists between the growth of glaciers and the existence of steppe conditions.

The loess of America.

The loess of America is very similar both in nature and distribution to that of Europe. In disregard of contours, absence of stratification, and finally in its fossils, it bears all the characters of an aeolian deposit. It is spread in a thin covering over uplands and valleys alike, but is thickest and coarsest along the river courses, especially those of the main south-flowing rivers such as the Mississippi and Missouri, on the east sides of which, some distance away from the bluffs, it has a very remarkable development. It overlies the older drift-sheets, and extends far south beyond their margins almost to the Gulf of Mexico, covering the greater part of Illinois, Iowa, and Nebraska, and the states to the south of them. It thins out in the direction of the Atlantic, and does not occur east of the Mississippi basin. This is in perfect harmony with absence of the loess on the Atlantic margin of Europe, where the presence of moist winds probably hindered its formation. Significant also is the fact that the American loess dies out northward even where not cut off by the newer drift. There is but little of it on the pre-Wisconsin drift of Minnesota and neighbouring parts of Iowa and Wisconsin.

The paha-ridges.

An extremely interesting variation in the general mode of occurrence of the loess as a uniform cloak or mantle covering the inequalities of the ground is to be found in the paha-ridges, found in parts of North-eastern Iowa and North-western Illinois. These are elliptical knolls or short ridges of loess rising in some cases 10 metres or more above the surrounding plains, which are free from loess. Some of them have a nucleus of rock or glacial material, but others appear to be composed

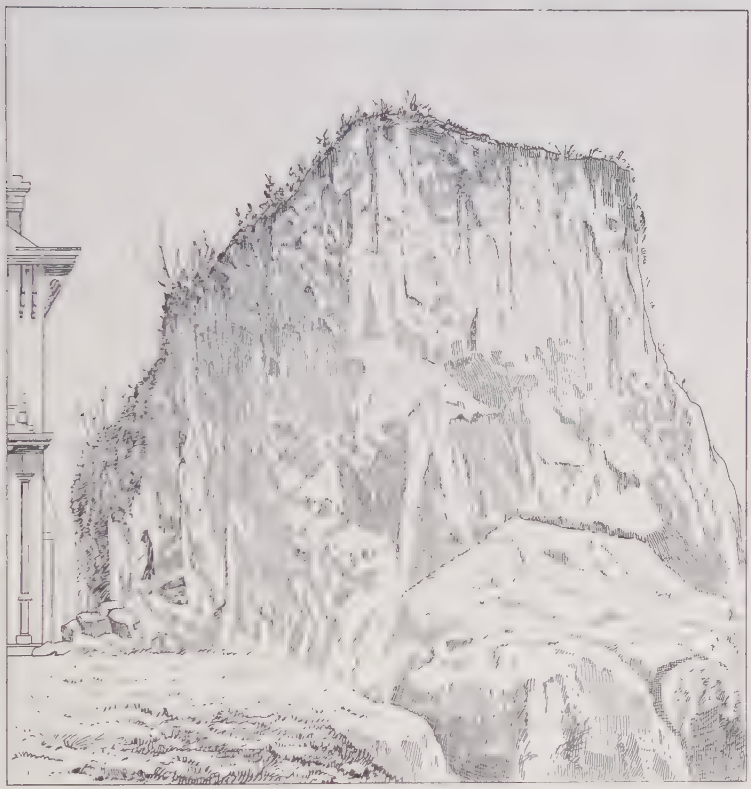

FIG. 69.—Sketch of a loess bluff in Iowa, to show the characteristic vertical jointing. (After M'Gee.)

of loess throughout right down to the level of the plain. They have a general trend in conformity with the direction of the prevalent wind, which is westerly. Those with a core of rock or boulder-clay have but little loess at the western end compared with that at the eastern. Shimek [1] has suggested that the elevations which formed the nuclei of the paha were the first to be drained and present conditions suitable to the growth of a vegetation capable of retaining dust.

Prevalent winds and origin of material.

Many facts in connexion with the American loess suggest that during its formation westerly winds were the prevalent ones. Hills are everywhere much more thickly covered on their eastern than on their western slopes. In particular the occurrence of great thicknesses of loess to the east of the main river valleys, the alluvial flats of which supplied abundant material, points in this direction. Leverett [2] is of opinion, however, that a considerable part of the material is far travelled, being derived from the great plains east of the Rocky Mountains, which are so arid and thinly covered with vegetation as to afford a large amount of fine material to be gathered by the winds. It certainly thins out to the east in a manner suggesting a westerly origin. If, however, we remember that here, as in Europe and Asia, the Quaternary steppes were probably merely an extension, due to a general change of climate conditions, of those of the present day, it will be seen that there is every reason that the American loess should thicken westward where the steppe conditions were more intense, just as it thickens eastward in Europe.

The Quaternary steppes an extension of those of the present day.

The molluscan fauna.

The study of the fossil remains of the American loess has not as yet advanced very far. Little or nothing is known of its mammalian fauna. Some admirable investigations of the molluscan faunas have, however, been made by Shimek.[3] He finds that the molluscs of the loess are, with few exceptions, similar to those occupying the same districts at the present day, but show a distinct tendency towards depauperation. They are represented by smaller, thicker-walled varieties such as at the present day characterise the more barren western portions of the country. Here again we see the effect of the eastward extension of steppe conditions referred to above.

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[1] B. Shimek, *Proc. Iowa Acad. Science,* vol. xv. p. 121 (1909).

[2] Frank Leverett, "Comparison of North American and European Glacial Deposits," *Zeitschrift für Gletscherkunde,* Bd. iv. p. 327 (1910).

[3] B. Shimek, "The Distribution of Loess Fossils," *Journ. of Geology,* vol. vii. p. 122 (1899).

Relation to the glacial drifts.

The relation of the American loess to the glacial deposits is very similar to that found to obtain in Europe. It overlies the outer and older drift (Kansan and Illinoian) and is completely wanting on the surface of the newer drift (Wisconsin). In fact, it can be seen passing beneath the Wisconsin drift in central and eastern Illinois, and as far east as south central Ohio. It is thus intermediate in age between the Illinoian and Wisconsin. The relation of the loess to the problematical Iowan drift has been discussed in Chapter VIII., and on account of the doubt which has recently been thrown on the whole of this question, no further reference will be made to it here.

The pre-Illinoian loess.

A very interesting point is the discovery of pre-Illinoian loess. This occurs in the area of the Yarmouth interglacial deposits which lie between the Kansan and Illinoian till-sheets in their region of overlap south of the driftless area (see p. 163). It has nowhere been seen in contact with the typical Yarmouth deposits, so that its relation to them is unknown. The best exposures are in sections along the banks of the Mississippi near Rock Island, where they have been studied by Udden. This loess is similar in appearance to that on the surface in the same region, but it bears evidence of its greater age in being more indurated, as well as in its stratigraphical position.[1]

If this loess is actually on the horizon of the Yarmouth deposits, it goes a long way towards establishing their interglacial character, which has been frequently called in question (see p. 164).

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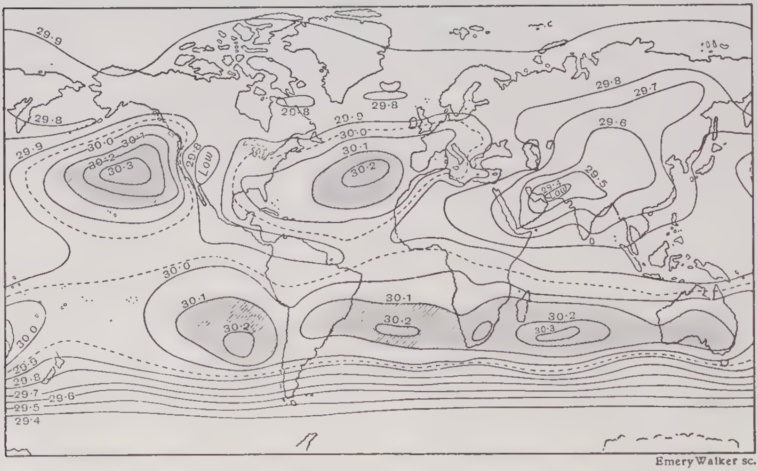
[1] Leverett, *Zeitschrift für Gletscherkunde*, Bd. iv. p. 275 (1910).

The high-pressure belts.

On consulting Mr. Buchan's monthly charts of the distribution of pressure over the earth's surface, it will be seen that, broadly speaking, there are two belts of high pressure extending round the globe north and south of the tropics. The existence of these, though greatly modified by geographical conditions, is not determined by the latter. It is primarily due to the distribution of sun-heat according to latitude. These high-pressure belts are, in fact, areas of descending air, part of which goes to feed the trade-winds, and which are themselves fed by the upper return currents or anti-trades. They are anti-cyclonic in character and characterised by dry climatic conditions. Considering the southern belt first, as it is more clearly defined, we notice its climatic effect wherever it crosses the land in the production of desert or steppe conditions. Thus Australia, the Kalahari, and the pampas of the Argentine all lie along its course. Dryness of climate is characteristic of all these regions in spite of the neighbourhood of great oceans over which active evaporation is taking place. It is perfectly



Emery Walker sc.

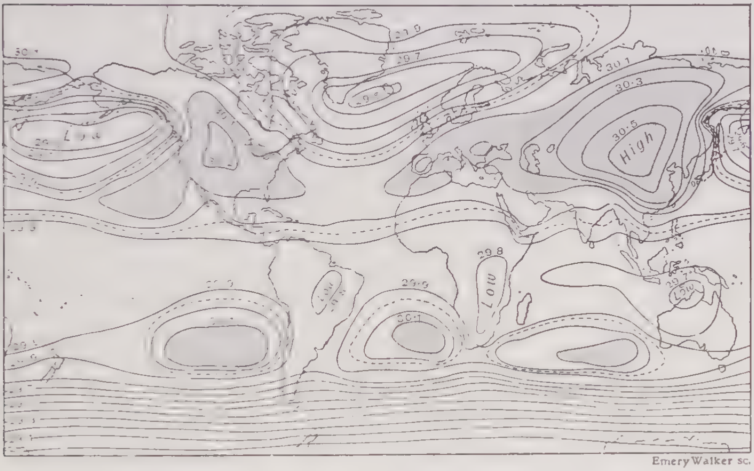
FIG. 70.—Isobaric chart of the world for July, representing the distribution of the belts of high pressure during the northern summer. (After Alex. Buchan.)

Coincidence of desert and steppe conditions with the southern belt.

clear that there is in these latitudes a distinct tendency, which is primarily independent of the relations of sea and land, towards high pressures and the descent of bodies of dry air.

Stability of the belts over the oceans.

Now, a study of the same charts will show that the portions of these high-pressure belts which lie over the ocean are much more stable than those over the continents. The latter tend to become broken up in summer owing to the heating effect of the land, which produces ascending currents. On the other hand, the reduced contrast between the seasons characteristic of the oceans tends to the permanence and continuity of the high-pressure belt.



Emery Walker sc.

Fig. 71.—Isobaric chart of the world for January, representing the distribution of the belts of high pressure during the southern summer. (After Alex. Buchan.)

Irregularity of the northern belt.

Owing to the larger areas of land in the northern hemisphere, the modifications of the corresponding belt as regards permanence and continuity are much more marked. Indeed, if it were not for the clearness of the relations in the southern hemisphere it would be nearly impossible to interpret those of the northern. That there is, however, such a belt is fairly obvious from the charts, and it also appears to have a greater tendency to permanence over the oceans. Over Asia and America it is in summer entirely broken up, while on the other hand it is intensified over these continents in the winter months. Contrast between the seasons due to the presence of large land areas is here, as in the southern hemisphere, obviously hostile to the permanence of the belts.

Coincidence of the loess with the high-pressure belt.

Now the Quaternary loess lies along a belt stretching round the northern hemisphere, this belt being in continuity with and merely an extension of the districts where the climate is still sufficiently dry for its formation. A general coincidence of the dry climates indicated by this deposit with the belt of high pressure, though much modified by local conditions, is obvious here as in the southern hemisphere, and is too marked to be a matter of chance. It is clear that any conditions tending to the persistence of the high-pressure belt over the land during summer, or even to its less pronounced destruction, must tend also towards an extension of the area of loess deposition. This consideration may possibly open up the way to a better explanation of the remarkable association of loess-formation with the Quaternary Glaciation, but more facts are needed before it becomes profitable to speculate further on the subject.

CHAPTER XI

THE QUATERNARY MAMMALS

Classification—Mammals now characteristic of the arctic tundras—The Lemmings—Their habits and present and past distribution—The Arctic Fox—The Variable Hare—The Reindeer—The Musk-Ox—The Glutton and Elk—Mammals now characteristic of the eastern steppes—The Jerboa—The Susliks—The Bobac—The Pika or Tailless Hare—The Corsac Fox—Pallas's Cat—The Saiga Antelope—The Dschiggetai—The Wild Horse—Quaternary mammals now inhabiting warmer climates—The Lion and Hyaena—Extinct Quaternary mammals—Richness of the Quaternary fauna—Extinction a basis for zoning—Classification of the Quaternary Elephants—*E. meridionalis*, *E. antiquus*, and *E. primigenius*—Classification of the Quaternary Rhinoceroses—The Hippopotamus—Hippopotamus deposits in the Sicilian caves—Probable explanation.

In discussing the characteristics of the Quaternary mammals we shall consider them under the following classes:

(1) Mammals which are now characteristic of the arctic tundras.
(2) Mammals which are now characteristic of the steppes.
(3) Mammals which have at the present day a southern distribution.
(4) Extinct mammals.

Section I.—Characteristic Mammals of the Arctic Tundras

The tundras of Northern Europe and Asia and the barren grounds of North America form together a well-defined botanical and zoological region of the earth's surface, characterised by the severity of its climate and the absence of trees. Mosses and lichens form the prevailing vegetation, and the subsoil is permanently frozen to a depth of many feet. In winter vast areas are covered with snow beneath which land, river, lake, and morass are alike frost-bound. In summer, on the advent of the warm southerly winds, the coating of snow vanishes, a thin surface layer of soil is thawed by the intense heat of the sun, mosses and grasses spring up everywhere, and herds of reindeer and other hardy animals, which have been wintering in the woods to the south, migrate northwards over the plains, feeding on the scanty vegetation.

The fauna of the tundras contains few species, but these are very characteristic.

It will easily be conceived that the fauna of this bleak and desolate stretch of country, frost-bound in winter and to a large extent impassable morass in summer, will be marked not only by the fewness of its species, but also by their highly specialised character. Nehring enumerates six species as being peculiarly characteristic of the arctic tundras, namely :

1. The Banded Lemming, *Myodes torquatus*, Pall.
2. The Siberian or Obi Lemming, *Myodes obensis*, Brants.
3. The Arctic Fox, *Canis lagopus*, L.
4. The Variable Hare, *Lepus variabilis*, Pall.
5. The Reindeer, *Cervus tarandus*, L.
6. The Musk-Ox, *Ovibos moschatus*, Gmel.

The Banded Lemming.

The Banded Lemming (*Myodes, Lemmus* or *Dicrostonyx*[1] *torquatus*) is the most characteristic land mammal of the treeless arctic region, none of the other northern mammals being so exclusively high northern. Its principal home is North Siberia, whence it extends over the neighbouring islands of the Arctic Sea and into North-eastern Europe. The climate of North-west Russia and Scandinavia is apparently too mild for it, its place being here taken by the Norwegian lemming, *M. norvegicus* (*M. lemmus*, L.). It is also found in the arctic districts of North America.[1] Like many other arctic animals, it secures invisibility in the winter by turning white.[2]

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[1] The Banded Lemming (*Dicrostonyx*) differs from the true Lemming in the absence of well-marked conchs to the ears.

When in this condition its fore-feet are also furnished with double claws, which disappear in summer. These are supposed to be developed for the purpose of digging. None of the lemmings, however, construct deep holes, and in this respect they differ markedly from the rodents of the steppe districts. Indeed such burrowing would be quite impossible in the frozen subsoil of the countries they inhabit.

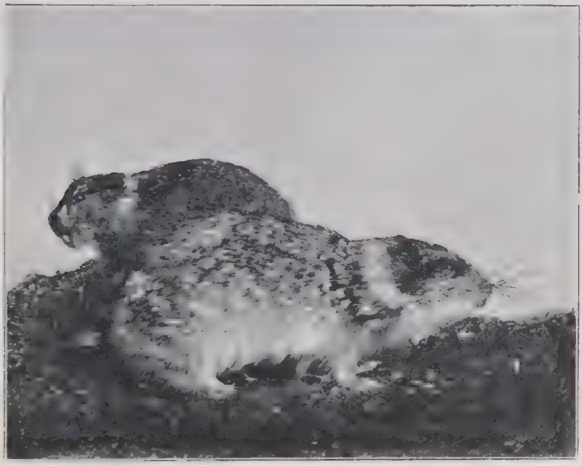

FIG. 72.—The Banded Lemming, *Myodes torquatus*, from a specimen in the British Museum.

The *Siberian Lemming* (*Myodes* or *Lemmus obensis*), sometimes referred to as the Common Lemming, has a distribution very similar to that of the Banded Lemming, but extends slightly farther south. It lives

The Siberian Lemming.

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[1] The American species, *M. hudsonius* and *M. groenlandicus*, formerly regarded as distinct species, have been recently proved to be identical with *M. torquatus*. See Cousa, *Geol. Survey of the Territories*, Bd. xi. p. 241.

[2] The change of colour seems to be brought about as a result of the stimulus of cold on the individual. Captain Ross, in 1835, showed that a captive lemming kept in a room in winter did not change colour until it was exposed to the cold. The power of reacting to the stimulus in this way has, of course, been acquired in the process of natural selection.

side by side with the Banded Lemming in the same country, but, as a general rule, keeps more to the lower ground than the latter species, which shows a decided preference for the higher rocky or stony districts.

Their former wide distribution in Central Europe.

Remains of these two species of lemming have been found in Germany, Belgium, France, England, Austria-Hungary, and Russian Poland. This widespread distribution and the abundance of the remains in certain localities are in themselves proof that the lemming formerly occupied the districts where its bones are found, but all doubt has been set aside by the finding of young individuals in association with full-grown ones, and by the occurrence of the latter side by side with other arctic animals.

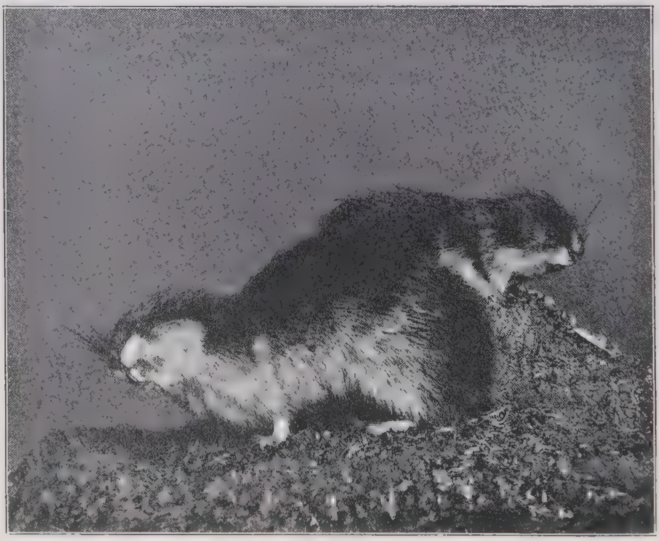


FIG. 73.—The Siberian Lemming, *Myodes obensis*, from a specimen in the British Museum.

The migratory habits of the Lemming.

The extraordinary periodic migrations of the lemming have been cited as an argument against the assumption that they lived in the localities in which their remains have been found. These migrations have been more especially studied in the case of the Norwegian species (*Myodes lemmus*, L.). The ordinary home of these animals is in the mountains, where they will dwell quietly for many years, multiplying in an extraordinary manner until the country teems with them. Then suddenly a sort of unrest seems to spread amongst them. Swarms of them descend to the plains, where they travel in a straight line towards the sea, heedless of all obstacles, eating their way through cornfields, and destroying all crops that happen to come in the line of their onward march. Thousands fall victims to the birds and beasts of prey that follow in their wake, and still more are drowned in the rivers and lakes they attempt to cross. Nevertheless, the survivors press on until they reach the sea, into which they plunge headlong and swim outwards until they perish. A romantic theory ascribes this extraordinary act of self-destruction to an instinctive search for the lost Atlantis. Whatever the meaning of it, it is clear that migrations of this kind might account for the distribution of lemming remains far from the districts where they live and breed. It is inconceivable, however, that any migration of the banded lemming could extend from its present area of distribution to Germany, France, and England. Moreover, the occurrence of remains of young lemmings could not be explained by migration.

The lemming remains of Thiede and Westeregeln.

In the gypsum quarries at Thiede, made famous by the researches of Nehring, lemming remains are very numerous, being found chiefly in the lower strata. They are especially abundant 24 to 30 feet from the top, but occur from 16 or 18 feet down to 40 feet. In the higher levels (16-24 feet) they occur very sporadically, and above 14 feet not at all. This dying out upwards is supposed by Nehring to indicate a gradual withdrawal, but the rare upper occurrences on the same level as the steppe rodents he ascribes to migration from adjoining mountainous districts.

In the Westeregeln Quarry there is no true tundra horizon, the remains of lemming occurring very sporadically and mostly on the same level as the very numerous steppe rodents found there. They are ascribed by Nehring to autumnal migration from the Harz Mountains.

In the Elizabeth Hole near Neumühle, in Bavarian Upper-Franconia, the lemming remains were only found in the deeper deposits, deeper than the remains of the Cave Bear and other diluvial animals. The Banded Lemming appears especially to be limited to the deepest cave strata, while *Myodes obensis* reaches farther up.

Norwegian Lemming.

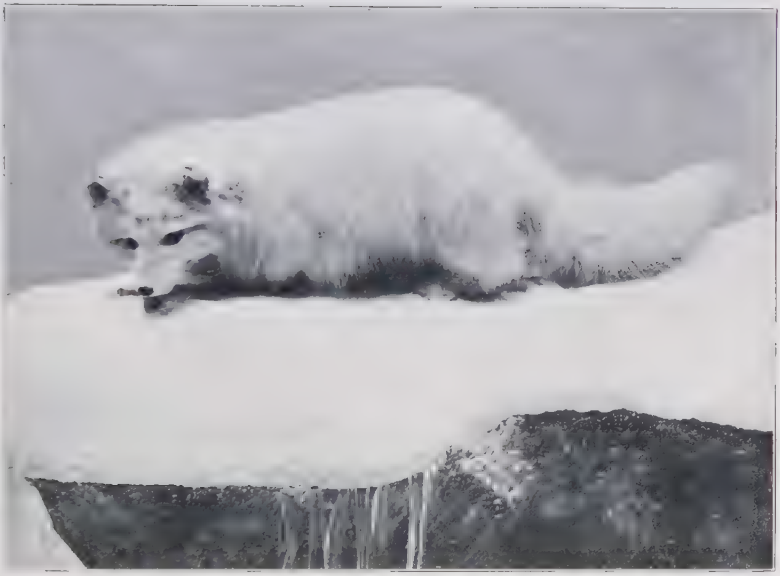
The Norwegian Lemming (*Myodes lemmus*, L.), which, although not strictly a tundra form, we have considered here, has been obtained by Mr. Abbot from the ossiferous fissure near Igtham, Kent. Remains of *Myodes torquatus* were obtained from the same fissure. Lemming remains have also been obtained from some other caverns in Great Britain and also from river-strata.

The Arctic Fox.

The Arctic Fox or Ice-Fox (*Canis lagopus*, L.) is a characteristic inhabitant of the tundras, and for its existence is chiefly dependent on the lemming. It is the smallest of all known foxes and lives only in the coldest parts of the Arctic zone, never extending farther south than the 60th parallel of latitude, whereas its occurrence is, as far as is known, unlimited towards the north. It is a decided wood-hater, and never penetrates the forest belt except where strips of treeless land occur, appearing to thrive better the more wild and barren the country. Its favourite habitat is in open rocky ground, where it finds shelter among the clefts. Like the lemming it changes its coat with the season, being white in winter and in summer a greyish brown.

Remains of the Arctic Fox have been found in association with those of the lemming in the lower deposits of the Thiede gypsum pits. One of these finds had a peculiarly beautiful significance. Some 24 feet beneath the upper surface were several well-preserved skeletons of lemming, and in their immediate neighbourhood two skeletons of young Arctic Foxes, still with their milk

PLATE XV.



THE ARCTIC FOX (*VULPES LAGOPUS*) IN WINTER COAT.

From a specimen in the British Museum.

To face p. 226.

teeth. Whether the lemmings were brought as food to the young ice-foxes, or were merely overwhelmed with them by a flood, it is pretty clear that they lived in the same district as the ice-foxes, since these latter had their milk teeth, and hence must have met their death in summer, a fact which excludes any recourse to autumnal migration as a method of introduction for the lemmings.

The Variable Hare.

The Variable Hare or Snow Hare (*Lepus variabilis*) is a very ill-defined species, and attempts have been repeatedly made to divide it into several sub-species. Like the Arctic Fox and Banded Lemming it turns white in winter. It is, according to Nehring, very difficult to refer fossil hare remains to their species, so that they are of little value as a basis for climatic conclusions. He however considers certain bones found in the lower deposits of the Thiede gypsum pit to be those of *Lepus variabilis*.

The Reindeer.

The Reindeer (*Cervus tarandus*) is on the whole a tundra dweller, the structure of its foot showing an adaptation to moor and snow surfaces. Two races are indeed distinguishable, namely, the smaller Tundra-Reindeer, which lives entirely on lichens and ranges into the extreme northern latitudes, and the larger Wood-Reindeer, which feeds partly on grass. These, however, cannot be sharply separated from one another and freely invade one another's territory, the tundra-reindeer migrating south into the woods in winter, and the wood-reindeer moving north on to the tundras in summer. The so-called woods in which the latter species occurs are composed of relatively low and sparsely scattered trees, and are quite unlike any of the lofty woods of middle Europe.

According to Professor Boyd Dawkins the reindeer had at a comparatively recent period a much more southerly distribution than at present. It appears to have been hunted during historic times in the north of Scotland. In Asia in 1780 it extended along the Urals to the foot of the Caucasus. It now has a much more restricted range, and is gradually being pushed north on the approach of civilized man. It is found in the north of America as well as in Europe-Asia.

The reindeer is one of the commonest and most widely known of Pleistocene mammals. It spread over the greater part of Europe during the Ice Age, extending even to the south of France. Its remains occur in abundance in caverns, river gravels and other deposits in the British Isles, and according to Boyd Dawkins are also referable to two races, the larger being the *Cervus bucklandi* of Owen, and the smaller the *Cervus guettardi* of Cuvier.

The Musk-Ox.

The Musk-Ox (*Ovibos moschatus*) is now confined to the northern portions of the barren grounds of North America and the unglaciated regions of N. Greenland. Its thoroughly Arctic nature is shown not only by the extremely high latitudes which it attains, but also by the limitation of its southern range. Although it has undoubtedly been driven north in places by the advance of man towards the poles, yet it nowhere comes as far south as the wood-boundary. In spite of its southerly migrations it reaches in the west of North America only to the polar circle, and in the east, in the treeless region of Hudson's Bay, to the 60th parallel. In its avoidance of wooded districts it shows a certain similarity to the ice-fox.

The musk-ox formerly had a wide distribution throughout the tundras of the Old World, although it now no longer occurs there. It has been found fossil in the ground-ice beds of Eschscholtz Bay, from which remains of mammoth, elk, reindeer, horse and bison have also been obtained. Pallas found it in the tundras between the Obi and Lena, and there are several other records of its remains having come to light in Northern Asia.

In Pleistocene times it was widely distributed throughout Central Europe and Great Britain. The most southerly discoveries of its fossil remains are those of Lartet in the department of Oise, the environs of Paris, and on the banks of the Vézère. In Great Britain, according to Boyd Dawkins, it has been found in the gravels of the River Avon near the Somerset and Wiltshire border, near Maidenhead on the banks of the Thames, and at Green St. Green in Kent.

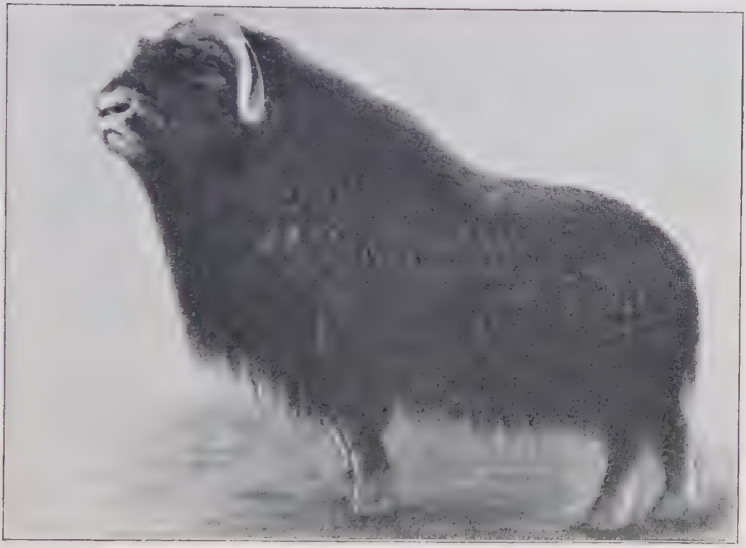


FIG. 74.—The Musk-Ox, *Ovibos moschatus*, from the publications of the Field Columbian Museum.

Among animals with a decided northerly range, yet not so exclusively high-northern or so markedly characteristic of the actual tundras, the following may be mentioned :—

1. The Wolverine or Glutton (*Gulo luscus*, L., or *Gulo borealis*).
2. The Elk or Moose (*Alces malchis*, Gray).

The Glutton or Wolverine, according to Boyd Dawkins, ranges at the present day through the colder The Glutton.

regions of North America, inhabiting alike the districts of the elk, the reindeer, and the musk-ox, and extending as far north as Melville Island in latitude 75°. According to Audubon it occurs as far south as Jefferson County, U.S.A., in latitude 42°-46°. It ranges also throughout Northern Asia, and in Europe inhabits the northern parts of Russia, Sweden, and Norway.

During the Ice Age the Glutton had a Central European distribution. It occurred abundantly in the caverns at Liège and also in the Bears' Den at Gailenreuth. In Britain it has been obtained from Banwel and Bleadon caves, and also from one of the caves at Gower, S. Wales.

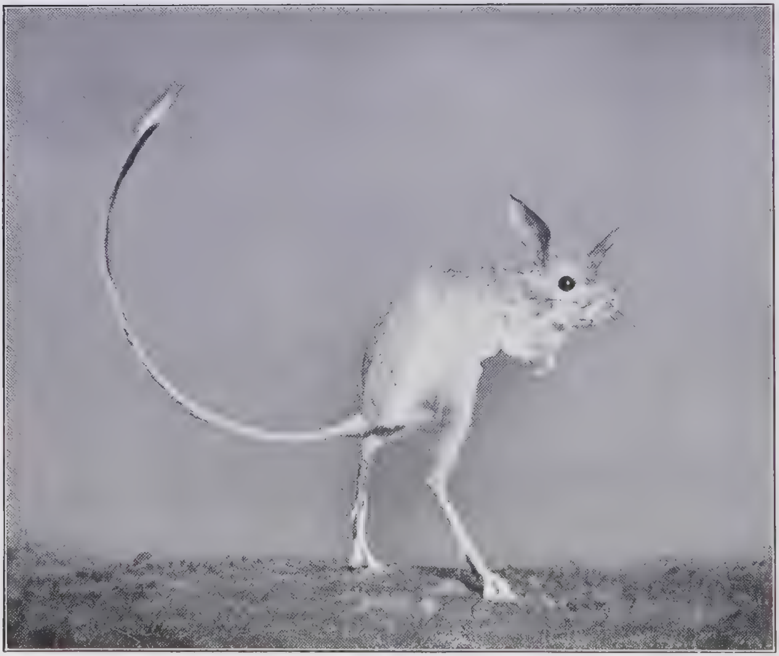
The Elk.

The Elk or Moose is at present a native of those northern parts of Asia, America, and Europe, not occupied by the reindeer. It is known under the former name in Norway and under the latter in Canada. It has been found in Great Britain in the cave of Llandebie.

SECTION II.—CHARACTERISTIC MAMMALS OF THE EASTERN STEPPES

The European Pleistocene mammals which at the present day are most eminently characteristic of, and in some cases absolutely confined to, the Russian and Siberian steppes are the following:—

1. The Jerboa, *Alactaga jaculus*, Pall.
2. The Red Suslik, *Spermophilus rufescens*, K. and Bl.
3. The Mugosaric Suslik, *S. mugosaricus*, Licht.
4. The Fawn-coloured Suslik, *S. fulvus*, Licht.
5. The Bobac or Steppe-marmot, *Arctomys bobac*, Schreb.
6. The Tailless Hare or Pika, *Lagomys pusillus*, Pall.
7. The Hamster, *Cricetus phaeus*, Pall, *C. arenarius*, Pall, etc.
8. Voles, *Arvicola*, several species.
9. The Corsac Fox, *Canis corsac*, L.
10. Pallas's Cat, *Felis manul*, Pall.
11. The Saiga Antilope, *Antelope saiga*, Pall.
12. The Dschiggetai or Asiatic Wild Ass, *Equus hemionus*, Pall.
13. The Wild Horse, *Equus caballus ferus*, Nel.



THE ARMENIAN JERBOA (*ALACTAGA WILLIAMSI*), VAN, ARMENIA.

From a specimen in the British Museum.

To face p. 231.

The Jerboa.

The Jerboas (*Alactaga* or *Dipus*) are a well-marked genus, exhibiting characters of such pronounced adaptation to steppe conditions that it can almost be said of them that their existence in any other kind of surroundings is impossible. The extreme development of the hind limbs and tail enable the Jerboas to travel at enormous velocities over the level grassy or sandy plains. The movement of the limbs during locomotion is so rapid that the eye cannot follow their action and gets the impression of aerial flight, hence the specific names, *jaculus*, *sagitta*, *telum*, which have been applied to them. They progress by enormous leaps, and their speed is often so great that it is said to be impossible to overtake them on horseback. The front limbs are little developed, and are mainly used as hands. There is a general resemblance in form to the kangaroos which inhabit the similar steppe and desert districts of Australia. The Jerboas are nocturnal and social animals, dwelling in burrows, which they construct in the sandy and loamy soil of the steppes. The burrows of some of the species, for example the Kirghiz Jerboa, are very complicated, having several entrances radiating from a central chamber, and are usually inhabited by two or three pairs of animals. Their habit of burrowing is of the greatest importance in the economy of their lives, as it enables them to sleep through the severities of the Asiatic winter.

The Greater Jerboa (*Alactaga jaculus*) inhabits the steppes of European Russia and the neighbouring parts of Asia. It is strictly limited to the steppe belt, and does not extend north of it, having, however, the most northerly and westerly range of all the Jerboas. Its most westerly recorded station is the town of Orel, and it extends south to the Dnieper or possibly to the Danube. It is especially abundant and large in the steppe-district of the Southern Urals near Slatousk and Orenberg, where it has been described by Lichtenstein under the name of *Dipus decumanus*. It is found in the steppes of Ischim and Irtysch in south-west Siberia, but its eastern limit is at present unknown.

This Jerboa is not a very shy animal, and lives near frequented roads, cultivated fields, and gardens. Its distribution is not therefore likely to have been limited by the encroachments of man. It is the most characteristic animal of the sub-Arctic steppes.

Remains of *Alactaga jaculus* have been found by Nehring at Westeregeln, Quedlinburg, Thiede, Gera, Posneck, Saalfeld and Würzburg, and by Woldrich at Zurlawitz. According to Fritsch and Kafka it also occurs abundantly in the loess near Prague.

The Dwarf Jerboa (*Alactaga acontion*, Pall.), which has a more southerly distribution than *A. jaculus*, has not been found in the Pleistocene deposits of Middle Europe.

The Suslik.

The Susliks or Pouched[1] Marmots (*Spermophilus*) are all burrowing animals, inhabiting open and steppe-like districts, where they live together in colonies. The burrows are of great depth, and in winter the animals subsist on the large stores of food which they accumulate therein during the summer months. *Spermophilus citillus*, the so-called Common Pouched Marmot, occurs especially in the steppe-like districts of Galicia, Hungary, and South Russia, but is found also in suitable localities in Silesia, in eastern Bohemia, in Moravia, and in Lower Austria. With regard to climate, it is continental like most of the susliks, but it still exists in those different parts of Middle Europe which approximate to the climate of Russia. It is not therefore so markedly a steppe-form as the other species of the genus. From this Brandt[2] distinguishes a number of species of which the three enumerated in the list above have been found fossil in Middle Europe. With regard to the doubt that exists concerning the specific subdivisions, Nehring quotes from Eversmann a passage of which the following is a literal translation :—

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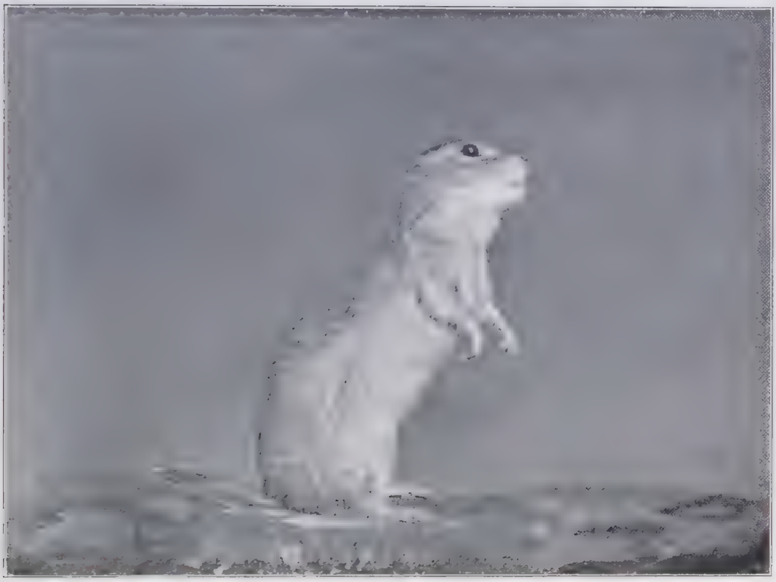
[1] Because of the cheek pouches which these animals possess in common with their relatives the Chipmunks.

[2] J. F. Brandt, "Observations sur les différentes espèces de Sousliks de Russie," etc., *Bull. de l'Acad. Imp. des Sciences de St-Pétersbourg*, tome ii. Nos. 23 and 24 (1843).



THE COMMON SUSLIK (*SPERMOPHILUS CITILLUS*), RUSSIA.

From a specimen in the British Museum.

To face p. 232.

> If we take the Susliks (Citelli), which occur in all steppes and which were formerly erroneously regarded as one species, all kinds have different stretches of country for their habitats. Of the Susliks of the eastern steppes I cannot express a definite opinion, except merely thus far, that they are specifically very different from those of the western steppes. Of these latter, which I know accurately, *Arctomys undulatus* (=*Spermophilus rufescens*, Blas.), for example, inhabits the stretch between the 56th and 50th parallels of latitude, farther south they no longer appear; there they are replaced by *Arctomys fulvus* (=*Spermophilus fulvus*) and *Arctomys mugosaricus* (=*Spermophilus mugosaricus*). The same is the case with the Jerboas, also an animal form which is peculiar to the steppes; thus *Dipus jaculus* (=*Alactaga jaculus*), for example, belongs to the stretch between the 54th and 48th parallels: then or even sooner begins the four-times-smaller *Dipus acontion* (=*A. acontion*), and extends almost to the 44th parallel, where still other species replace it, which I collected in my travels near Buckharia and which Herr Prof. Lichtenstein has described and figured.
>
> To return to our Susliks: *Arctomys undulatus* of the north makes its holes obliquely in the earth at a slope of about 50°, lives gregariously, is an active animal, and plays in the hot sunshine. *Arctomys mugosaricus* makes its holes far more obliquely, goes alone in the steppes after food and moves very slowly, so that one can easily overtake it. *Arctomys fulvus*, on the other hand, makes its holes quite perpendicularly in the ground, goes forth alone, and apparently far from its home into the steppe around, and travels with the greatest speed in leaps and bounds, so that one sees it flying by something like a polecat.

Fossil remains of *Spermophilus rufescens* occur, according to Nehring, at Westeregeln, Quedlinburg, Thiede, Jena, Saalfeld, Posneck, Oppurg, Neumühle, Neu-Titschein, Prague, Türmitz, Zuzlawitz, Würzburg, Tübingen, Praunheim near Frankfurt-a.-M., and Curve near Wiesbaden. In his opinion certain remains of *Spermophilus* found in France, Belgium and England probably also belong to this species, but their minuter specific differences have not yet been investigated.

The identification of the fossil remains of *S. mugosaricus* and *S. fulvus* is not a matter of such certainty, but Nehring has found remains of a small suslik, probably referable to the former species, at Westeregeln and at Nussdorf near Vienna, while a larger species, which appears to agree with *S. fulvus*, has been observed at Weilbach near Frankfurt-a.-M., and at Neumühle in Upper Franconia.

The Bobac or Steppe Marmot.

The Bobac or Steppe Marmot (*Arctomys bobac*) is a near relative of the well-known Alpine Marmot, being nevertheless specifically distinct from it and inhabiting the Volga-Ural Steppe, of which it is one of the characteristic animals. It avoids wooded country and dwells in open grassy and rocky ground. Though inhabiting the same districts as the Suslik, it is never to be seen, according to Eversmann, in the immediate neighbourhood of the latter. The Suslik likes the loamy soil of the level steppes, but the Bobac must have hilly and stony ground. It never, however, ascends the mountain beyond the lower limit of wood growth. Its range in the region between the Volga and Ural Mountains is not very extensive, reaching only from about the 54th to the 50th parallel of latitude. According to Brandt it occurs in the Central Asiatic Steppes south to the Himalayas, Karchar and Tibet, and east to Kamchatka and East Siberia. The River Dnieper seems to form its present western limit. The Bobac is very shy, and does not go far from its hole. It lives in large colonies and forms burrows, each tenanted by a single family. A sentry keeps watch from the mound in front of the burrow and gives the alarm on the approach of danger. In winter as many as 10 or 15 animals occupy the one burrow, where they sleep from equinox to equinox, apparently without break, and certainly without taking food.

Nehring found undoubted remains of the Bobac at Westeregeln, and it has been recorded from some half-dozen other places in Middle Europe. Hensel referred the abundant remains at Gera to this species, but Liebe regarded them as belonging to a common ancestor of *Arctomys bobac* and *A. marmotta*, the Alpine Marmot.

Many of the diluvial finds of marmot are, according to Nehring, probably referable to the last-mentioned species *A. marmotta*, which inhabits the mountain regions of Middle Europe above the belt of close and lofty woods, and is very similar in its habits to the Bobac. Marmot remains have been found in Germany, France, Switzerland and Belgium.

The Pika or Tailless Hare.

The Pika or Tailless Hare (*Lagomys*) has but a slight footing in Europe at the present day, the main area of distribution of the genus being Central and North Asia. Of the numerous species, *Lagomys pusillus* has the most westerly range, reaching in places into Europe and occurring in the steppes along the Volga. In Pleistocene times it extended to Middle Europe, and has been found fossil in numerous localities. At Westeregeln, Nehring found a complete skeleton and numerous other remains associated with the Jerboa and other steppe animals.

A skeleton found in Kent's Hole is said to belong to this species, and its remains have been proved by Abbot and Newton in the fissure at Igtham in Kent.

Hamsters.

In addition to the common Hamster (*Cricetus vulgaris* or *frumentarius*) there are found in the South Russian and neighbouring Asiatic steppes still smaller species (*C. phaeus*, *C. arenarius*, *C. songarus*), which are characteristic of these districts. A small species, at any rate nearly related, if not referable to one of the above, has been obtained fossil in several localities in Middle Europe by Nehring and Woldrich.

Field-mice.

Several species of field-mouse (*Arvicola*), now limited to the Eastern Steppe-districts, have been found by Nehring along with the other steppe animals at Westeregeln and Thiede, and also occur abundantly in other localities in Middle Europe, such as Gera and Zuzlawitz.

The Corsac Fox.

The Corsac Fox (*Canis corsac*) is, like the Arctic Fox, a small species, and is as thorough a frequenter of the steppes as the latter of the tundras. It is found in all the steppes of Tartary from the Volga and the Caspian Sea through the whole of Middle Asia to Lake Baikal. It is not yet distinctly proved to have been a member of the Pleistocene fauna of Middle Europe, but its distribution apparently once extended to Moravia and Bohemia, and according to Woldrich the small fox called by him *Vulpes meridionalis*, and found at Zuzlawitz and Neu-Titschein, is probably the ancestor of the Corsac.

Pallas's Cat.

Pallas's Cat (*Felis manul*) takes in the Asiatic Steppes in some degree the place of the Wild Cat (*Felis catus*) of the woods of Europe, from which its remains are not easily distinguishable. In cases where remains of the Wild Cat are found in association with steppe animals, Nehring thinks they are probably referable to the former species.

The Saiga Antelope.

The Saiga Antelope (*Antilope saiga*) is a characteristic animal of the South Russian and South-west Siberian Steppes. In the last century it extended to the eastern boundary of the old kingdom of Poland, but since then it has withdrawn more and more into the trans-Volgan Steppes. According to Helmerson it often migrates in summer-time so far north along the eastern foot of the Urals as to come into contact with the area of distribution of the reindeer. In winter, on the other hand, it moves south into Turkestan into the margin of the region occupied by *Antilope subgutturosa*.

The valuable investigations of Gaudry have established the remarkable fact that the Saiga antelope once extended to Western France. On the Charente, in deposits of the so-called Reindeer Age, its remains are so abundant and characteristic as to leave no doubt as to its identification. It occurs also in Belgium, where it has been recorded by Dupont among the fauna of the Trou de Chaleux, in the neighbourhood of Dinant-sur-Meuse.

The Dschiggetai or Asiatic Wild Ass (*Equus hemionus*) is an inhabitant of the Aralo-Caspian and Kirghiz steppes, where it is known under the name "Kulan." It probably had a wider and more westerly distribution formerly. It is a slender animal, endowed with great speed. Nehring considers its remains to have been proved for Gera, Quedlinburg and Westeregeln. He is of opinion that other remains of the wild ass found in association with steppe mammals also belong to this species. *Equus asinus*, to which they have commonly been referred, has its home in North-east Africa.

The Dschiggetai.

The Wild Horse (*Equus caballus ferus*) occurred in the Volga-Ural Steppes about a century ago, Pallas having observed it there in small herds at that time. It was formerly abundant in Middle Europe, occurring in the deposits of Westeregeln and Thiede, and in the loess of Remagen on the Rhine, as well as in numerous caves.

The Wild Horse.

SECTION III.—QUATERNARY ANIMALS NOW INHABITING WARMER CLIMATES

According to Boyd Dawkins only two of the Pleistocene mammals of Europe are now confined to more southerly and warmer climates; they are—

Felis spelaea, a variety of *Felis leo*.
Hyaena spelaea ,, ,, *Hyaena crocuta*.

The Quaternary Hippopotamus might, however, be included in this category, as there seems to be some doubt as to whether it is distinct from *H. amphibius*, which is now confined to Africa.

The Lion (*Felis leo*) now occupies the whole of Africa, with the exception of Egypt and Cape Colony, while in Asia a maneless variety inhabits the valley of the Tigris and Euphrates and the districts bordering on the Persian Gulf. Its former wider distribution has become much restricted by the advance of civilization.

The Lion.

According to the testimony of Herodotus and other writers it lived in Europe in historic times, and there is every reason to suppose that but for man it would at the present day have a much more northerly range. Its presence in Pleistocene deposits is therefore hardly a matter for surprise, even where it is found associated with northern animals.

The Cave Lion (*Felis spelaea*, Goldfuss) has been found in many cavern deposits throughout the whole of temperate and Southern Europe and also in Great Britain, as far north as Yorkshire, but not in Scotland or Ireland. Its bones occurred in enormous quantities in the western half of the Mendip Hills in Somerset. The reason, according to Boyd Dawkins, is to be found in the fact that the caves in these hills "command fertile valleys to the north, and look out towards the south and west over a plain which in Post-glacial[1] times occupied a large portion of the Bristol Channel. Around them were the feeding grounds of incalculable numbers of Reindeer, Bison, and Horse, of the Mammoth and tichorhine Rhinoceros, and, therefore, we might expect to find the carnivora present in great abundance."

The Hyaena.

The Cave Hyaena (*H. spelaea*) was a variety of *H. crocuta* now confined to South Africa. It had a wide distribution in Pleistocene times, from the Altai Mountains, throughout Asia and the whole of Europe, into France and England.

Felis antiqua of the Pleistocene was a variety of the leopard (*F. pardus*), which now has a wide range in countries with both cold and warm climates.

SECTION IV.—EXTINCT QUATERNARY MAMMALS

Richness of Quaternary Fauna.

The Pleistocene Period witnessed the extinction of a number of important mammalian forms, which during its early stages were not only abundant but had an exceedingly wide distribution. The fauna of Europe, and indeed of Asia, America, and Australia as well, was then far richer and more varied than that occupying the same districts at the present day. Much of the change was no doubt due to man, but much also must be ascribed to the extraordinary and apparently world-wide climatic oscillations which characterised this remarkable epoch. The actual effect of these revolutions we have little means of gauging, but there can be no doubt that the changes which caused Europe to be occupied at different stages by the faunas of the steppes and tundras of Asia must so considerably have disturbed the balance of animal life as to lead to the extinction of many species.

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[1] In the sense of subsequent to the glaciation of the neighbourhood.

Extinction as a basis for zoning.

These extinct species have an interest peculiarly their own, for their successive disappearance affords a rude method of zoning the quaternary deposits. Thus, for example, the various species of elephant became extinct in Europe at very different periods, and the occurrence of any species in a deposit affords a sort of later limit for the time of its formation. A similar zonal value attaches to the species of rhinoceros, and there are a few other animals the remains of which have a like significance.

There is an immense literature dealing with the quaternary fossil elephants, an adequate treatment of which would occupy more space than is permissible within the limits of the present chapter. It is only possible to give the generally accepted classification and some discussion of the range of the various species in time.

Classification of the Quaternary Elephants.

Three species of elephant are recognised as eminently characteristic of the late Pliocene and Quaternary of Europe; they are

Elephas meridionalis, Nesti.
Elephas antiquus, Falc.
Elephas primigenius, Blumenb.

These are largely distinguished and in many cases entirely identified by the characters of their teeth, the differences in which cannot be adequately discussed here. The species became extinct in the order mentioned, and we have a much less accurate knowledge of the older than of *E. primigenius*, which is the species commonly known as the Mammoth. Complete carcases of the latter have been found embedded in the ground-ice and frozen mud of Siberia, so that we can form an idea of its softer parts which are not elsewhere preserved. An investigation has even been made of the contents of its stomach, from which it appears that it lived on the low-growing herbage of the plains, and did not, as is often supposed to be the case with elephants, require extensive forests for its support. It was covered with long hair as a protection against the cold climates in which it existed.

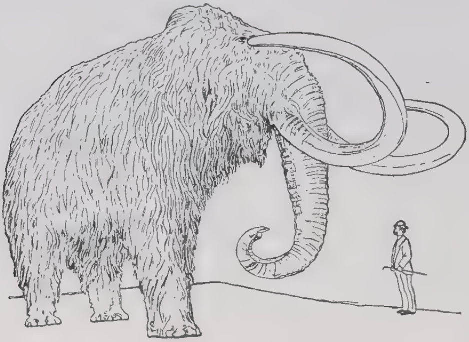

Fig. 75.—The Mammoth, *Elephas primigenius*, from the stuffed specimen in the St. Petersburg Museum. (After Hoernes.)

In the case of the other species a knowledge of their size and character has only been acquired with some difficulty by the occasional finding of skulls, tusks, and other parts of the body. The knowledge thus gained has, however, entirely justified the original establishment of the species on dental characters alone. Moreover, according to Falconer "the teeth from which the names of *Elephas primigenius*, *E. antiquus*, and *E. meridionalis* have been derived, represent such pronounced differences, that with the knowledge of the well-known specific characters which distinguish the dental character of the two living species, there can be no possible reason in not accepting their very divergent aspects as true morphological differences."

The size of the quaternary elephants appears to have been extremely variable, but *Elephas antiquus* was generally both stouter and taller than the Mammoth, and *E. meridionalis* seems to have surpassed them both.

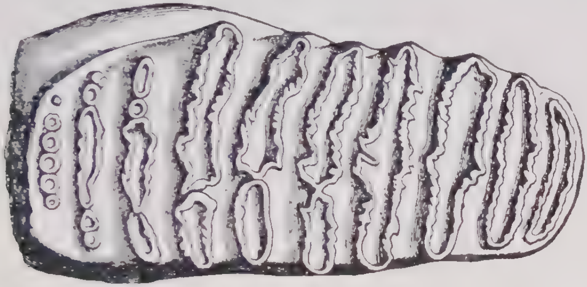

Fig. 76.—*Elephas meridionalis*, last lower molar but one. (From Sollas's *Ancient Hunters*. After Lyell.)

According to Falconer the latter species must have been fully 14 feet high at the shoulder. The cause of the prolonged survival of the mammoth was probably due to its superior lightness and activity, which, with its thick covering of hair, would serve it in good stead during the severe and variable conditions of the Ice Age.

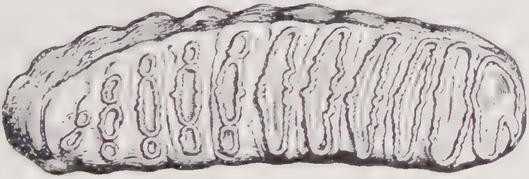

Fig. 77.—*Elephas antiquus*, last lower molar but one. (From Sollas's *Ancient Hunters*. After Lyell.)

Elephas meridionalis is generally regarded as being a characteristic Pliocene species, whereas *E. antiquus* and *E. primigenius* occur mostly in Pleistocene deposits. *E. antiquus* has, however, been obtained from the Red Crag of Norfolk, and all three species occur in the

Cromer Forest Bed. The classification of the latter deposit as strictly Pliocene is however, to say the least of it, doubtful. On the continent *E. meridionalis* is certainly not entirely of Pliocene age, for it has been obtained from interglacial deposits in the Alps. On the other hand it has not been found in England in any deposits of recognised Pleistocene age, and it certainly did not survive the Ice Age. Remains of *E. antiquus* and *E. primigenius* are frequently found in association in deposits of glacial age, and the mammoth almost certainly lived on into post-glacial times. The brick-earths of the Thames valley yield both species.

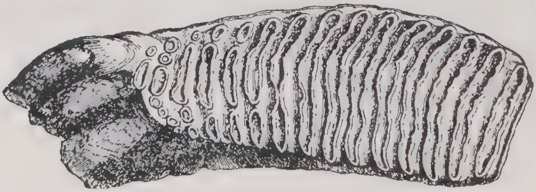

FIG. 78.—*Elephas primigenius*, last lower molar but one. (From Sollas's *Ancient Hunters*. After Lyell.)

Although all these elephants are now extinct, a study of their distribution and association with other forms have given them a certain value as indicators of climatic conditions. *Elephas meridionalis* is a characteristic Pliocene form, and is most commonly associated with a southern group of animals. It most certainly indicates a climate at least as mild as that of Western Europe at the present day. *E. antiquus* is perhaps somewhat less southern, but compared with *E. primigenius* it is distinctly so. The mammoth has left unmistakable proof of its residence in the arctic regions of both the old and new worlds, whereas in the north-west of Europe not a single instance of remains of *E. antiquus* having been found north of the 54th parallel of latitude is on record.

As a form apparently distinct from any of the above species, Brandt and Woldrich mention *Elephas priscus*, Goldf., which appears to have been related to the living African elephant, *E. africanus.* Its remains have been found at Madrid and at Wittenberg in Prussia.

Elephas meridionalis.

Elephas meridionalis is the characteristic species of the Pliocene of Middle and South Europe, occurring in the Forest Bed of Norfolk and in the Upper Pliocene deposits of the Val d'Arno and the Auvergne. It also persisted into Pleistocene times as is shown by its occurrence in the interglacial deposits of the Alps. The molars may have as many as 13-14 ridges. According to Leith Adams (*British Fossil Elephants*, p. 232) the crowns are very broad, the columns short as compared with *E. antiquus*, and generally as compared with *E. primigenius*; the enamel of the discs is thick and rarely crimped, but usually uneven, looped, or channelled, and the plates are wide apart and have thick wedges of cement.

Elephas antiquus.

Elephas antiquus, the straight-tusked elephant, occurs in the late Pliocene and early Pleistocene deposits of Europe, and appears in beds of the latter horizon in India, where it has been called *E. nomadicus.* It has narrow, elongated grinding teeth with comparatively few plates. The skull is peculiar in having a sort of overfolded ridge on its frontal portion, forming an overhanging fold on the forehead. None of the later forms show this character, so that it is unlikely that they are descended from *E. antiquus.* This species had a wide distribution and a considerable range in time. It occurs in the Red Crag and in the Norfolk Forest bed, and is abundant in the Pleistocene deposits of England, such as the brick-earth of the Thames Valley, being commonly associated with the mammoth.

Elephas primigenius.

Elephas primigenius—the mammoth—represents the highest pitch of evolution attained by the elephants, being in some respects in advance even of the Indian elephant. The teeth are extremely complex, and the third molar may have as many as 18 to 27 ridges. This complexity, according to Andrews, represents the culmination of a long series of changes traceable in the evolution of the *Elephantidae*, all tending to increase the efficiency of the molars as grinding organs. The great size, and especially height of the crown, gives them a prolonged period of wear, while the numerous alternating plates of enamel, dentine, and cement, of different degrees of hardness, ensure that the grinding surface will remain sufficiently rough for the purpose throughout the period during which the tooth remains in use.

The classification of the Pleistocene rhinoceroses

Classification of the Quaternary Rhinoceroses.

appears to be rather confused, the synonymy of the various species being far from obvious. Brandt and Woldrich mention three diluvial or quaternary species of rhinoceros (*Atelodus*). These are:

1. *R. antiquitatis*, Brandt = *R. antiquitatis*, Blumenb. = *R. tichorhinus*, Cuv., Fischer = *R. jourdani*, Lartet and Chantre.
2. *R. merckii*, Brandt = *R. merckii*, Jaeg. Kaup. = *R. hemitoechus* and *etruscus*, Falconer.
3. *R. leptorhinus*, Pomel. = *R. leptorhinus*, Cuv. = *R. megarhinus*, Christol.

But, according to Boyd Dawkins, *R. etruscus*, Falc., is distinct from *R. hemitoechus*, Falc., which latter is, according to him, equivalent to *R. leptorhinus*, Owen. If, however, as appears to be the case, *R. leptorhinus*, Cuv., is equivalent to the clearly distinct species *R. megarhinus*, Christol., then it would seem advisable to drop the term *R. leptorhinus*, Owen. Boyd Dawkins considers *R. leptorhinus*, Cuv., to include *R. megarhinus*, Christol., *R. etruscus*, and *R. hemitoechus*. His classification of the British fossil rhinoceroses is as follows:

1. *R. schleiermacheri* (Red Crag of Suffolk).
2. *R. etruscus*, Falc. = *R. merckii*, Von Meyer = *R. merckii*, Lartet.
3. *R. megarhinus*, Christol. = *R. kirchbergensis*, Jäger.
4. *R. hemitoechus*, Falc. = *R. leptorhinus*, Owen.
5. *R. tichorhinus*, Cuv. = *R. antiquitatis*, Blumenb.

The only essential difference between these two classifications is that Brandt and Woldrich do not separate *R. hemitoechus*, Falc., from *R. etruscus*, Falc. They seem, however, to be distinct, and we may regard the quaternary rhinoceroses of north-western Europe as represented by the four species: (1) *R. etruscus*, Falc.; (2) *R. megarhinus*, Christol.; (3) *R. hemitoechus*, Falc.; and (4) *R. tichorhinus*, Cuv.

Rhinoceros etruscus.

(1) *Rhinoceros etruscus*, Falc., which appears to be equivalent to the *R. merckii* of various authors, was

first accurately described by Boyd Dawkins, though the name had been previously suggested by Falconer. Unlike *R. megarhinus* it had its nasals supported by an osseous partition, which partly separated one nostril from the other, and strengthened the basement of the anterior horn. Its upper true molars are distinguished from those of any other British species by the lowness of their crowns, the abruptly tapering form of the colles, and the stoutness of the guard in the anterior aspect.

This species is very abundant in the Pliocene deposits of the Val d' Arno near Florence, and is the typical rhinoceros of the Norfolk Forest-bed. It also ranged in preglacial times through France and Spain. Its distribution indicates that it required a warmer climate than *R. tichorhinus.* Like the other British fossil rhinoceroses it was two-horned.

Rhinoceros megarhinus.

(2) *Rhinoceros megarhinus*, Christol., was a great, slender-limbed rhinoceros with largely-developed nasals. It had no trace of a cloison or bony partition between the nostrils, contrasting sharply in this respect with *R. tichorhinus.*

In Pliocene and Pleistocene times it was distributed over Italy, France, Germany, and England (river deposits of Gray's Thurrock in the Thames Valley and the Cromer Forest Bed). Compared with *R. tichorhinus* its distribution shows it to have been a distinctly temperate species. Of the two it was the older, and is found in association with the Pliocene mastodons and with *Elephas meridionalis.*

Rhinoceros hemitoechus.

(3) *Rhinoceros hemitoechus*, Falc., is described by Boyd Dawkins under the name of *R. leptorhinus*, Owen. It is characterised by the partial ossification of the septum of the nostrils, by the slenderness of the bones, and by certain peculiarities in the dentition. In regard to the ossification of the septum it is intermediate between *R. tichorhinus* and *R. megarhinus.* As pointed out by Cuvier and emphasised by Boyd Dawkins, the development of this bony septum stands in direct relation to the horn development, and it is probable,

therefore, that in respect of the size of its anterior horn it was intermediate between the two above-named species.

R. hemitoechus has been found in a number of British caves, including those of Gower, and in the brick-earths of the Thames Valley.

Rhinoceros tichorhinus.

(4) *Rhinoceros tichorhinus*, Cuv., is characterised by the possession of an osseous septum which completely separates one nostril from the other, and indicates that the horns, like those of *R. etruscus*, were of unusual size and weight. The discovery of a carcass of this animal in the frozen sand of the Wilonji, a tributary of the Lena, proves that, unlike the existing species, its hide was without folds and was clothed with thick hair. This latter character has earned for it the title Woolly Rhinoceros, and was obviously an adaptation to the severity of the climate under which it lived.

The remains of *R. tichorhinus* are found in quaternary deposits from the Pyrenees and Alps throughout France, Germany and Russia, and Siberia, as far north as the shores of the Arctic Sea and east to Behring Straits. It is common in the river deposits and caves of Britain, and is the frequent companion of *Elephas primigenius*. Its remains are dredged abundantly from the Dogger Bank in the North Sea.

Dental characters of the Rhinoceroses.

A comparison of the dental character of these and other rhinoceroses made by Boyd Dawkins is of exceptional interest. He points out that *R. megarhinus* and *R. leptorhinus* possessed dental characteristics which are now shared among the widely divergent living species. *Rhinoceros etruscus*, on the other hand, points rather backwards than forwards in time, and its dental characters are represented only by the milk teeth of some of the rhinoceroses that lived after its extinction; these characters are found, on the other hand, in nearly all the Miocene species. *R. tichorhinus* differs considerably in dental characters from the other three species.

The classification adopted by Osborn[1] differs somewhat from that above outlined, but, as he does not give the authors of his species, it is impossible to gauge accurately the amount of disagreement. He refers the Pleistocene rhinoceroses to three species :

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[1] Henry Fairfield Osborn, *The Age of Mammals*. New York, 1910.

(1) *R. etruscus*, a small animal of Pliocene and early Pleistocene times, distinguished by brachyodont or short-crowned grinding teeth and long slender limbs, two horns, the larger of which is posterior, and the absence of cutting or front teeth.

(2) *R. megarhinus* (= *R. merckii*), the broad-nosed rhinoceros which succeeded *R. etruscus*, which it resembles in horn, limbs, and feet, and the absence of cutting teeth, the main difference being the possession of long-crowned or hypsodont grinding teeth.

(3) *R. antiquitatis* (= *R. tichorhinus*), a distinctly cold weather, steppe, and tundra form, which, like the foregoing, has no front teeth, but is distinguished from them by possessing a very large front and small posterior horn, thus really belonging to the modern African group Atelodus or Diceros.

Distinctness of *Rhinoceros tichorhinus*.

There is obviously a good deal of confusion in these various classifications, but the distinctness of *R. tichorhinus* comes out prominently. It is allied to the modern African rhinoceros (*Atelodus* or *Diceros*), while the remaining species form a group showing affinities to the Sumatran form (*Dicerorhinus*), but differing from it in the absence of cutting teeth. Although it is eminently desirable that the classification and synonymy of these forms should be cleared up, yet for the purposes of glacial geology it is fortunate that the most important point is the distinction of the cold climate form, *R. tichorhinus*, from the temperate and warm climate forms known as *R. merckii*, *R. megarhinus*, *R. etruscus*, etc.

The huge animal called *Elasmotherium sibiricum*, which lived in Siberia in Pleistocene times, was a near ally of the rhinoceroses, but differed remarkably in the structure of the cheek-teeth, which are tall-crowned, and show some approximation to those of the horses.

The hippopotamus.

Hippopotamus amphibius and *Hippopotamus liberiensis*, the two existing species of hippopotamus, are now confined to Africa, but in the Pleistocene and Pliocene periods the genus was widely spread over the Old World. The remains found most commonly in Europe indicate an animal of great size, and are frequently referred to as *Hippopotamus major*, but there is not any evidence for regarding this as a species distinct from *H. amphibius*. In the Pleistocene and Pliocene of India there are two species, *H. palaeindicus* and *H. sivalensis*, which differ from *H. amphibius* in the number and size of their incisors. *Hippopotamus pentlandi* was a dwarfed species, the remains of which have been found in enormous quantities in the caves and fissures of Sicily and Malta as well as in Italy. There was probably another still smaller form, *Hippopotamus minutus*, which occurred in the Mediterranean Islands.

The Palermo hippopotamus caves.

The enormous quantities of hippopotamus bones which have been unearthed in some of the Sicilian caves form one of the standing puzzles of quaternary geology. The most famous case is that of the caves of San Ciro and Maccagnone near Palermo. These caves are situated at a height of 220 feet above the sea in the cliffs of Hippurite limestone which surround the Pliocene plain of Palermo, and about 50 feet above this plain. According to Falconer[1] the cave of San Ciro had wave-worn and pholas-bored walls, and on the floor a deposit of sand with sea-shells and corals. The deposit which overlay this was, however, a subaerial breccia, and yielded enormous quantities of bones almost entirely of hippopotamus. In 1829, when there was a great demand for bones for the manufacture of lamp black for sugar refining, they were dug out and exported in large quantities. The remains of hundreds of individuals were actually counted, and thousands must have been removed. Representatives of every bone in the body were obtained, and were proved to belong to animals of all ages down to a foetus. The bone breccia also occurred outside the cave on either side to a distance of 85 yards from its mouth. The Grotto di Maccagnone showed similar phenomena.

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[1] H. Falconer, "On the Ossiferous Grotto di Maccagnone, near Palermo," *Quart. Journ. Geol. Soc.* xvi. p. 99 (1859).

Theory to account for them.

The explanation of this extraordinary accumulation of hippopotamus bones is probably to be found in the peculiar conditions which obtained in the Mediterranean Basin during the Ice Age. The distribution of certain of the Pleistocene mammals throughout the islands of Malta, Sardinia, Cyprus, etc., and certain considerations as regards the snow-line in the Alps (see p. 149), seem to require a lower sea-level than at present. Moreover, as the evaporation in the Mediterranean exceeds the supply of water from the inflowing rivers, it is clear that if ever the general level of the sea sank sufficiently low to leave the Straits of Gibraltar dry, the basin must have had an interior drainage, and consequently been occupied by a salt lake. As a matter of fact, it is clear from the configuration of the sea-bottom that there must have been two lakes, one in the eastern and one in the western part of the basin. The eastern lake, which received the waters of a number of large rivers, including the Danube and the Nile, was probably fresh and overflowed into the western. Now the Palermo hippopotamus remains occur in a subaerial breccia which Prestwich[1] has correlated, and very likely correctly, with the rubble drift of north-western Europe (see Chap. V.). This rubble-drift was not improbably a dry climate formation produced at the same time as the loess of central Europe. Whether, however, we regard the climate during the formation of the breccia as drier than at present or much the same, it would appear from the considerations mentioned above that we may conceive a state of affairs in which the smaller rivers flowing into the lakes would dry up along their lower courses during the summer months, as happens in many of the interior basins of Asia. The hippopotami living around the shores of the western or fresh water lake would ascend these streams in the wet season, and find themselves cut off in their upper reaches on the advent of the drier months. Ascending higher along the withering streams in search of water they would arrive, no doubt, at such localities as the Palermo cliffs and take refuge in the caves against the heat and drought. Many may have been thus trapped year after year and perished for want of water, leaving their bones to be covered up by the debris accumulating at the foot of the cliff.

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[1] J. Prestwich, "Submergence of Western Europe and the Mediterranean Coasts," *Phil. Trans.* vol. clxxxiv. pp. 903-984 (1893).

Hippopotamus remains occur frequently in Pliocene and Pleistocene deposits in north-western Europe, but none have as yet been discovered in eastern Europe or in Siberia. In England they occur in the Cromer Forest Bed, in the deposits of the Thames Valley, in "post-glacial" strata at Bedford, and in a number of caves. The frequent association of the hippopotamus with northern animals is rather difficult to understand, as it is the most pronouncedly southern of all the quaternary mammals of Europe.

CHAPTER XII

QUATERNARY MAN

The principles of zoning—Zonal subdivision of the Quaternary—Stone Age, Bronze Age, and Iron Age—Palaeolithic and Neolithic Periods—de Mortillet's classification of the Palaeolithic—The Eolithic Period—Older and Younger Palaeolithic—Chelléen—Acheuléen—Moustérien—Palaeolithic Art—Aurignacien—Solutréen—Magdalénien—Relation of the Palaeolithic Stages to the Ice Age—Nature of stations—Fauna—Stratigraphical evidence—The Neandertal, Grimaldi, and Crô-Magnon races—Continuity of industry in spite of change of race—Palaeolithic man in England—The elephant-trench at Dewlish—The preglacial hearths at Prah Sands—The Transition Period—Campignien, Tardenoisien, and Asylien—The Neolithic Period—Classification of Montelius.

On zoning.

INTO all geological problems there enters the question of zoning, the effort to get a time scale along which the different events in the world's history can be chronologically arranged. To effect this it is necessary to select fossils of common occurrence and wide distribution, which are in some way characteristic of each subdivision of the chronological scale. Now fossils which appear to have a zonal significance may have acquired it in different ways. They may be characteristic of certain horizons, merely because the conditions in the region where the deposits containing them were laid down became in some way suitable to their existence and encouraged their immigration from other regions. Zones established on such a basis have only a local, though it may be a widely local, value. As an example we may mention the attempted subdivision of the Quaternary into periods characterised respectively by Arctic, continental and wood faunas. A slightly better method is that which bases the time scale on the extinction or decline of certain species. Various geologists have endeavoured to use the extinct Pleistocene elephants and rhinoceroses for this purpose. Harmer's zoning of the Pliocene (Chap. IV.) is a combination of this method with that last mentioned. By far the most satisfactory result is, however, obtained when some form is discovered, which was in process of active evolution in the strata dealt with. Error due to a recurrence of type is in this case almost excluded, and we get much nearer an absolute scale than in those cases where the characteristic forms of each horizon are not related to one another, but have immigrated from other regions.

Now in dealing with the zonal subdivision of the Pleistocene we find ourselves in difficulty owing to the shortness of the period. The selection of some form which was in an extremely rapid state of evolution is rendered imperative. Man certainly fulfils this condition, but his fossil remains are exceedingly rare. Complications, moreover, arise owing to the burial customs introduced in the later stages of his development. Something has, however, been done in the direction of showing that the men of early Pleistocene times had a much more primitive skull development than those of a later period. The products of man's industry, however, form an even more legible record of his mental evolution than any preservation of his bones could ever afford, and it is in the study of these that the greatest advances have been made. Thus it was early recognised by archaeologists that the use of metals for the manufacture of implements and weapons marked a great advance on the use of stone, and among metals the employment of iron was clearly later than and replaced the use of bronze. Three periods were thus distinguished, namely—

Human implements as zonal fossils.

The Stone Age,
The Bronze Age,
The Iron Age,

which succeeded one another in the order named. It soon became apparent, however, that the Stone Age was, as regards duration, much the most important of the three; and in dealing with Pleistocene geology it is practically it alone that must be considered, since the Iron Age is largely historic, and the Bronze Age distinctly later than any of the geological phenomena with which we have to deal. The Stone Age itself has, however, proved capable of considerably more detailed subdivision, and, as time goes on, further advances seem likely to be made, so that it is very important to give here some account of what has already been accomplished in this direction.

Subdivision of the Stone Age.

For a long time past two subdivisions have been recognised, the Older Stone Age and the Younger Stone Age. For these Sir John Lubbock suggested the terms Palaeolithic and Neolithic, which are now in common use. The essential distinction between the two is the presence of ground and polished implements in the latter, and their almost complete absence in the former. In Britain, and indeed over the whole of Northern Europe, the Neolithic Period is cut off from the Palaeolithic by a great hiatus. There seem to be no indications of a passage from one of these stages of culture to the other. Man appears to have left the country in the Palaeolithic stage of his development and not returned until the Neolithic stage. Broadly speaking, the Neolithic implements always occur on the present surface, while the palaeoliths on the contrary are found embedded in ancient river gravels and the deeper strata of caves. The fauna associated with the Palaeolithic implements contains many species which are either extinct or have since withdrawn from Western Europe, while on the contrary the Neolithic fauna is very similar to that of the present day.

The Palaeolithic Period

To the great French archaeologist, G. de Mortillet,[1] we

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[1] Some years before the publication of de Mortillet's classification, Lartet, working in the caves of the Vézère, distinguished three types of industry: (1) that of Le Moustier, (2) that of Laugerie basse, and (3) that of Laugerie haute. These corresponded respectively to de Mortillet's Moustérien, Solutréen, and Magdalénien.

Subdivisions of the Palaeolithic Period.

owe the classification of Palaeolithic implements, which has rendered possible a further subdivision of the period. He distinguished six stages, the uppermost of which is regarded as possessing characters indicating a transition to the Neolithic culture. To these stages modern researches have added a seventh, the Aurignacien, which was indeed recognised by G. de Mortillet in his earlier classification, but on theoretical grounds placed wrongly in the succession, and finally rejected by him in the year 1872. Its proper position may now be regarded as clearly established, and the classification stands as follows :—

	Stage.	Characterised by
Younger Palaeolithic.	Tourassien.	Flat stag's horn harpoons. Decline of work in stone and bone. Supposed transition from Palaeolithic to Neolithic.
	Magdalénien.	Round stag's horn harpoons. Small and light flint implements. Awls. Development of bone implements and of the art of drawing.
	Solutréen.	Bay-leaf points and points with a shaft or tang. Highest development of stone-work.
	Aurignacien.	Elongated end-scrapers (Ger. *Krätzer*, Fr. *grattoir*), notched or hollow scrapers, knives, and boring points. First appearance of work in bone and horn and of the art of drawing.
Middle Palaeolithic.	Moustérien.	Points for use in the hand. Broad side-scrapers (Ger. *Schaber*, Fr. *racloir*). Broad and thick flakes worked only on one side. Disappearance of the *coup-de-poing*.
Older Palaeolithic.	Acheuléen.	Lighter and smaller *coups-de-poing*; finer work. Mixture of retouched stone implements with those merely rough hewn.
	Chelléen.	A single predominant type of stone implement, the *coup-de-poing*, thick and clumsy, both sides rough hewn.

Eoliths.

The Chelléen *coup-de-poing* was for a long time the earliest known product of the industry of man. Recently, however, a number of discoveries have been made tending to show that much more primitive types exist. These are known as eoliths. They have been found in deposits of Quaternary, Pliocene, Miocene, and even Oligocene age. Much doubt has been cast on their artificial origin, and the character of the implements certainly affords ground for scepticism. Taken altogether, however, it must be admitted that there is a large and growing mass of evidence for the existence of stone-working men far back into the Tertiary. Curiously enough, the famous Oligocene implements of Boncelles in Belgium, discovered by Rutot, seem as convincingly artificial as any Eolithic implements of later date. The discussion of this problem is, however, beyond the scope of the present volume, and we must content ourselves with giving a notion of the probable significance of these discoveries, by reproducing in Fig. 79 Penck's conception of the time relations during the Eolithic Period. It should be noted also that certain implements are known which are older than the Chelléen, and yet not to be confused with the problematic eoliths. These have been termed pre-Chelléen, and are simply hewn and retouched stone-flakes. They occur, among other places, at the base of the Palaeolithic

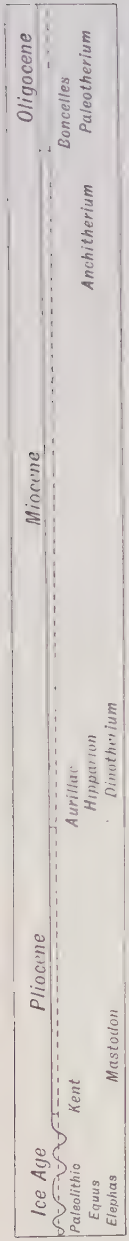


FIG. 79.—Diagram showing Penck's conception of the time-relations and climatic oscillations during the Palaeolithic and supposed Eolithic Periods. The Eolithic localities of Kent, Aurillac, and Boncelles are shown in their chronological positions. In the colder periods the curve descends below, and in the warmer periods rises above the dotted line, which represents the present climate. (After Penck.)

series in the classic locality of St. Acheul. Rutot has applied the term Strépyien to this phase.

The subdivision of the Palaeolithic into Older, Middle, and Younger, as indicated on the table, is based partly on the absence or presence of instruments made of bone, horn, and ivory. These first appear definitely in the Aurignacien. From the Chelléen and Acheuléen only stone implements are known, while the occurrence in a few cases of rudely worked bones in deposits of Moustérien age, foreshadows the more advanced development of this industry in the later periods.

Chelléen

The *coup-de-poing.*

The predominant type of implement in the Chelléen stage was the *coup-de-poing.* This was an almond- or lancet-shaped oval or triangular implement, with a thick base for holding in the hand, sharp edges, and a thinner point. It was made by striking flakes from an oval lump of flint, part of the original crust of which is often left on the thick base. It might have been used for stabbing, cutting and scraping, boring and digging, and when reversed could be employed as a hammer. It was, in fact, a sort of universal implement adapted for many primitive needs. The first conception of the type may have arisen through the accidental knocking of flakes off a flint knob.

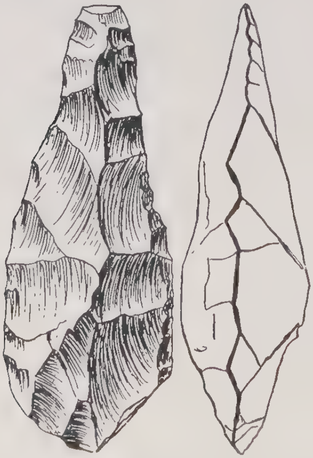
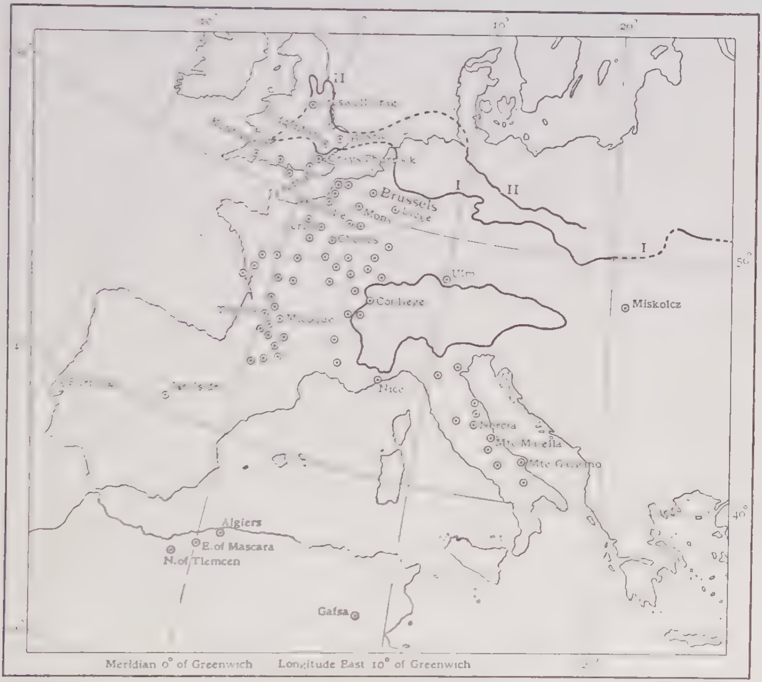


FIG. 80.—Chelléen *coup-de-poing*, from Chelles (× $\frac{1}{3}$); front and side views. (From Sollas's *Ancient Hunters.* After Chouquet.)

Associated with the Chelléen *coups-de-poing* proper there are occasionally found similar implements made out of a large flake instead of a whole flint knob. These are, however, rare, and are quite distinct from the later Moustérien points and scrapers.[1]

Acheuléen

The Acheuléen forms a transition stage between the Chelléen and Moustérien, and in it types similar to those of these two stages are found commingled. The Acheuléen *coup-de-poing* is, however, slighter and more delicately worked than that of the Chelléen. A broad flint flake has generally been employed in its manufacture



Emery Walker sc.

FIG. 81.—Map showing the known distribution of the Older Palaeolithic industry in Europe.

Positions of the stations, after Sollas. I., Limit of maximum glaciation; II., Limit of the newer drift.

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[1] Moritz Hoernes, *Natur und Urgeschichte des Menschen.* Vienna and Leipzig, 1909.

rather than a complete flint knob. It is more symmetrically and regularly formed, especially round the circumference, and is clearly an advance on the Chelléen type.

The Levallois flake.

With the Acheuléen *coup-de-poing* is found the Levallois flake, a one-sided oval and thin flake with marginal retouching round the original outer side. In the making of this flake the large flat side was the last formed. A flint nodule was first hewn into shape and then split into two parts with a powerful blow. This has been proved by Commont,[1] who has found working places where the Acheuléen and Moustérien men manufactured their implements, and by piecing the fragments together has demonstrated that the shaping of the convex side was effected before the flake was struck off the flint knob. The flakes were afterwards frequently retouched along the margin.

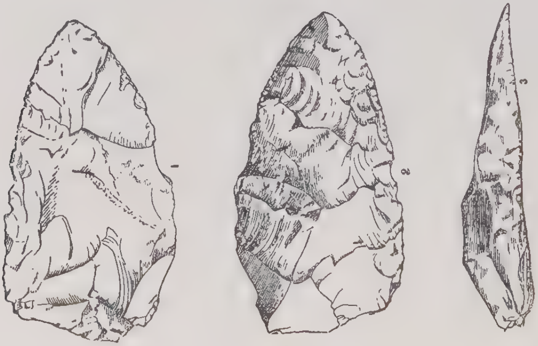

FIG. 82.—Levallois flake from Wolvercote, near Oxford, showing the flat and convex faces, and the side view (× $\frac{1}{5}$). (After Sollas.)

The Chelléen and Acheuléen *coups-de-poing* are known to have a wide distribution. They occur most frequently and abundantly in Western Europe, *i.e.* in France, Southern England, Belgium, Spain, and Portugal. They are also found in Italy, Algeria, Egypt, Somaliland, Syria, Palestine, India, Siberia, and North America.

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[1] V. Commont, "L'Industrie Moustérienne dans la Région du Nord de la France," *Congr. préhist. de France.* Paris, 1910. See also W. J. Sollas, *Ancient Hunters*, pp. 124 and 131. London, 1911.

In Middle and Eastern Europe they are wanting or, at least, extremely rare. There is indeed altogether a great rarity of Older Palaeolithic remains in these last mentioned regions.[1]

Moustérien

The Moustérien point

The Acheuléen is in some degree a transition stage and is omitted altogether by certain archaeologists, who date the Moustérien Period from the introduction of the Levallois flake. In the Moustérien proper, however, the *coup-de-poing* is entirely absent. The typical instrument is the Moustérien point, which is really a perfected Levallois flake, more symmetrical in shape and leaf-like or triangular in form. The inner or last formed face is generally left smooth, and the retouching done on the outer side. There is a saw-like edge formed by marginal retouching, which is wanting at the base of the point.

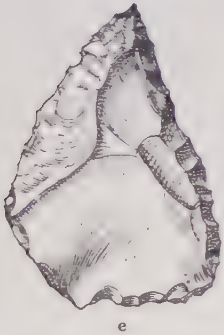

Fig. 83. — Moustérien point found associated with the Spy skeleton. (From Sollas's *Ancient Hunters*. After de Ruydt and Lohert.)

and scraper.

Associated with the Moustérien point occurs a semicircular or semioval scraper, the side-scraper, with a gently curved retouched edge approximately along the diameter of the semicircle.

The form of many implements of this stage is intermediate between the point and the scraper. Occasionally there occur notched or hollow-edged scrapers, with a retouched re-entrant margin well adapted for scraping round staff-shaped bodies of wood, horn, or bone. End-scrapers and boring-points also occur, but are not abundant or characteristic.

Distribution of the Moustérien.

The Moustérien is, like the Chelléen and Acheuléen, best developed in Western Europe, especially in France.

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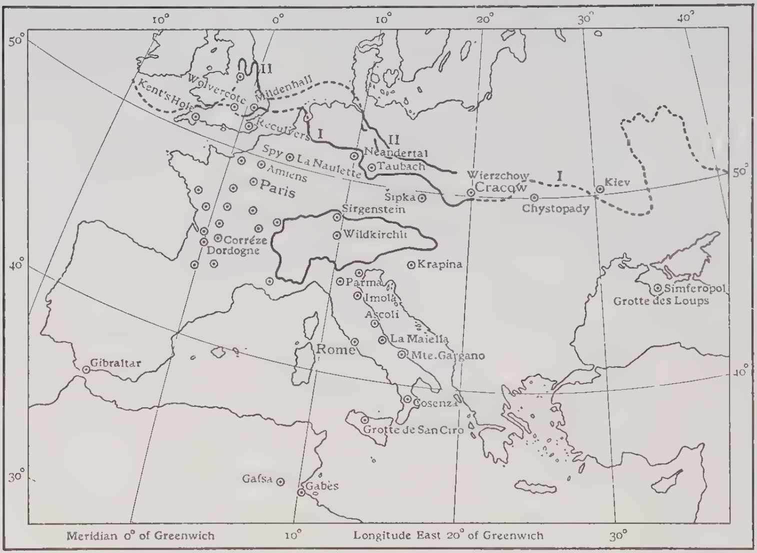
[1] M. Hoernes, *Natur und Urgeschichte des Menschen*, p. 153.

It occurs, however, also in other districts which were not glaciated during the Ice Age. Unlike the Chelléen it extends into Middle Europe, having been proved at Taubach near Weimar, in the Upper Danube district and at Krapina in Croatia. It is also found in North Africa and West Asia. The characters are, however, not so well marked as in the western region.



Emery Walker sc.

Fig. 84.—Map showing the known distribution of Moustérien stations in Europe.

Positions of the stations after Sollas. I., Limit of maximum glaciation; II., Limit of the newer drift.

Subdivision of the Younger Palaeolithic. Sculpture and drawing.

The subdivision of the Younger Palaeolithic is facilitated by the presence of implements of bone, which show a progressive development throughout the period. The existence of the arts of sculpture and drawing also affords a further principle of classification. This was first emphasised by Piette in his investigation of the caves of the Pyrenees and Southern France. Piette entirely put aside de Mortillet's classification, holding that stone implements afford no proper basis for the separation of the stages. In this he undoubtedly went too far. He, however, conferred a lasting benefit on archaeology by calling attention to the importance of art in the study of the Younger Palaeolithic Period, termed by him the Glyptic Period.[1] It had, of course, for a long time past been known that man, during the later portion of the Palaeolithic Period, had brought to a remarkable degree of perfection the art of drawing. Fragments of bone, horn and ivory had been obtained from the strata of this period, on which were depicted, with striking skill and a keen appreciation of their outstanding characteristics, many of the contemporary animals such as the reindeer and mammoth (Figs. 85, 86). It is worthy of note that our first knowledge of the covering of long hair possessed by the mammoth was obtained from these drawings, but the fact was for a long time discredited until finally confirmed by the discovery of an entire frozen carcass in Siberia.

A remarkable advance in the study of the art of Palaeolithic man was the finding of rock drawings on the walls of the caves. These were first noticed in Spain in 1878 by the Spanish nobleman Marcellino de Sautuolo, who, as a reward for his brilliant discovery, was made the laughing-stock of the archaeological world for over ten years. It was even suggested that the whole affair was a trick of the local clergy, designed to take in the French savants. Subsequent researches, however, revealed the existence of similar drawings in many of the French caves. They were shown to be overlain in places by a thick coating of transparent calc-sinter, or by cave-earth, so that practical joking was out of the question. Moreover, Daleau in the Grotte Pair-non-Pair, near Marcamps in the Gironde, showed that some of the drawings were overlain by undisturbed strata regarded by him as Magdalénien, but since shown to be of Upper Aurignacien Age. Moreover, the outlines of some of these drawings were filled in with ochre, fragments of

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[1] Glyptics, the art of engraving figures on stone.

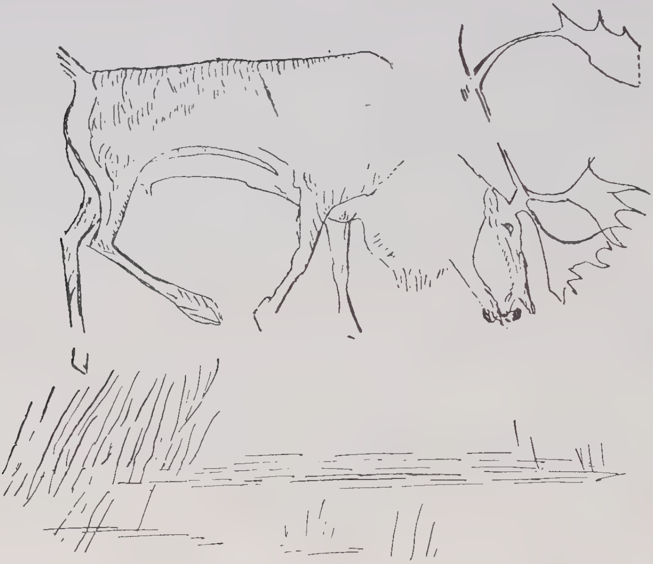

Fig. 85.—The grazing reindeer from the Kesslerloch, near Thayngen, Switzerland, engraved on a shaft straightener. (Original size, from Sollas's *Ancient Hunters,* after Mercks.)

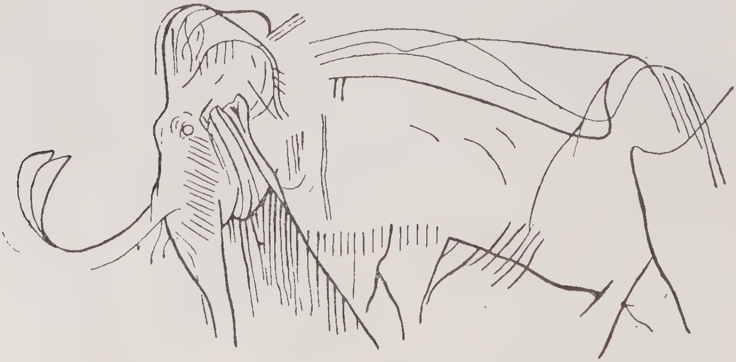

Fig. 86.—Mammoth engraved on ivory from La Madeleine ($\times\frac{2}{3}$, from Sollas's *Ancient Hunters.* (After Lartet and Christy.)

which were found in the strata of the cave. The

Palaeolithic age of these particular drawings was thus placed beyond question, and they carried with them the other less authenticated cases. In addition to the mammoth and reindeer, the wild goat, the bison and the horse are repeatedly depicted. Some pictures of young mammoths are particularly interesting. They appear to have been as round as a ball, and completely enveloped in their wool. The drawings, strange to say, often cover the walls in the very innermost recesses of the caves, where the light of day can never have penetrated.[1]

Sub-division of the Younger Palaeolithic.

Three phases of the Younger Palaeolithic have already been separated, and recent researches seem to indicate that even these are further subdivisible. The first of these stages is the Aurignacien, the last the Magdalénien. The art of working bone, which commenced in the Aurignacien, reached its culmination in the Magdalénien. The middle stage, or Solutréen, is of subsidiary importance, and is probably only a more or less local phase at the end of the Aurignacien. It is of interest, however, as marking the high-water mark of skill in the working of stone, the use of which was largely replaced by that of bone in the succeeding Magdalénien.

Aurignacien

Aurignacien implements.

In the Aurignacien several new types of implement, not known in the Older Palaeolithic Period, make their appearance. These are (1) the Chatelperron point, (2) the keeled or carinated scraper, (3) the beaked burin, and (4) the La Gravette point. The Chatelperron point, which makes its appearance in the Lower Aurignacien, is a curved, pointed flake with secondary flaking along one edge (Fig. 87). The keeled scraper, which does not seem to have been invented till the Middle Aurignacien, has a steep bevel edge at the end with channel-like secondary flaking. It is flat on one side and prominently keeled on the other (Fig. 88). The beaked burin, said

The Chatelperron point.

The keeled scraper.

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[1] M. Hoernes, *Der diluviale Mensch in Europa*, p. 54. Brunswick, 1903.

The La Gravette point.

to be an engraving tool, is a derivative of the keeled scraper. It is frequently fashioned like a scraper at the opposite end from the point, and has often a retouched notch at one side. The La Gravette point of the Upper Aurignacien is a long and thin cutting blade with secondary working along one edge (Fig. 89).[1]

Bone implements.

The Aurignacien Period witnessed the first general use of bone in the manufacture of implements. In the lower strata these are of a very rude type. The Middle Aurignacien, however, yields a well-formed and very characteristic implement, a bone point with a split or bifid base (Fig. 90). Shaft straighteners also

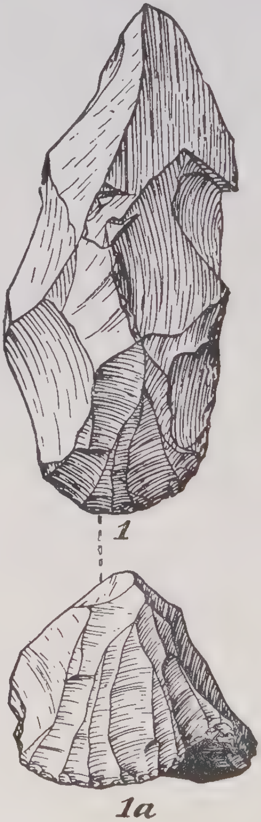

Fig. 88. — Keeled Aurignacien scraper from the lower hearths of La Coumba del Bouïtou, Corrèze. (From Sollas's *Ancient Hunters,* after Bardon and Bouyssonie, $\times \frac{3}{5}$.)

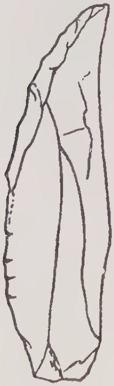

Fig. 87.—The Chatelperron point. (After Déchelette.)

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[1] W. J. Sollas, *Ancient Hunters,* pp. 216-218 (London, 1911). Joseph Déchelette, *Manuel d'archéologie,* vol. i. pp. 120-125 (Paris, 1910). L. Bardon, A. and J. Bouyssonie, "Grattoir caréné et ses dérivés à la Coumbo-del-Bouïtou (Corrèze)," *Rev. mensuelle de l'École d'Anthr. de Paris,* p. 401 (1906).

occur very like those of the later Magdalénien, but less ornamented.

Drawing.

Statuary.

Some wonderful advances have recently been made in the study of Aurignacien art, and it has been shown that in drawing and engraving they almost equalled the later Magdaléniens. Many of the drawings are coloured with ochre, and tubes for holding the pigment are found in the deposits. In the art of statuary they appear to have surpassed the Magdalénien hunters. Small statuettes, fashioned with considerable skill, are found in many of the deposits of Aurignacien age in different parts of Europe. These represent female figures of a peculiarity of form, which will perhaps be sufficiently described as the Hottentot Venus type. This type of figure is that of the bushmen of Africa, and the occurrence of these statuettes almost undoubtedly indicates African affinities in the Aurignacien race. The Aurignacien stations already known lie mainly in France, Belgium,

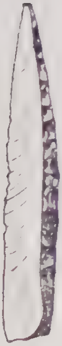

FIG. 89.—The La Gravette point. ($\times \frac{2}{3}$, after Déchelette.)

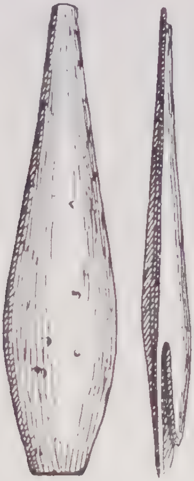

FIG. 90. — Aurignacien bone point with split base. ($\times \frac{1}{3}$, after Déchelette.)

and Western Germany (Lorraine), but there are a few in Austria which belong to this period.

Solutréen

Solutréen implements.

The laurel-leaf point.

The Solutréen Period is characterised by great perfection in the art of working stone. Some of the implements rival those of the Neolithic Period. Two forms are particularly characteristic, the laurel-leaf point and the tanged or shouldered point. The former is found throughout the Solutréen, the latter only in the uppermost deposits. The laurel-leaf point, which when long and narrow is termed the willow-leaf point, is a very beautiful implement with delicate and regular

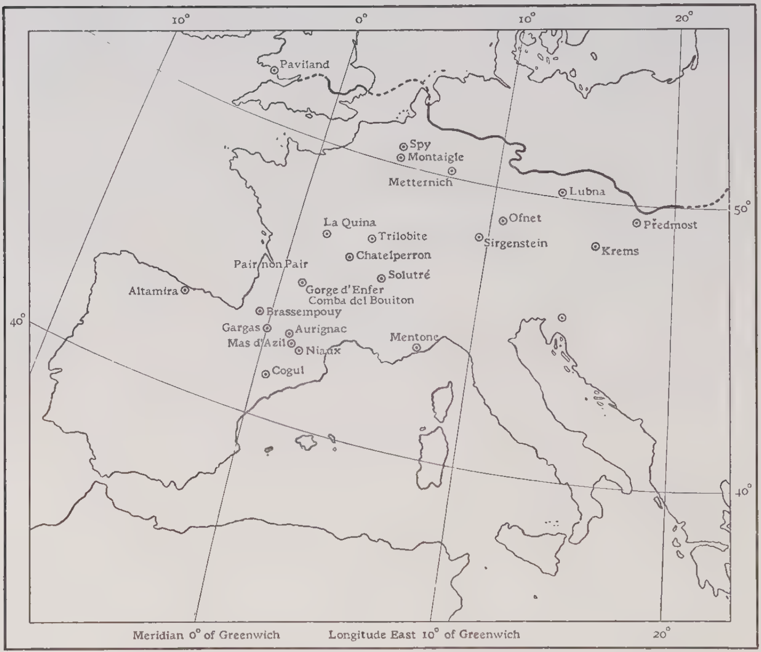

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FIG. 91.—Map showing the known distribution of Aurignacien stations in Europe. (Positions of the stations after Sollas; the black line shows the limit of the northern glaciation.)

channelled flaking (Fig. 92). Specimens have been found so thin as to be almost transparent. The most typical form of the tanged or shouldered point is also shown in Fig. 92. It is retouched on one side only, and when this side is placed uppermost the shoulder is generally on the right-hand side. In addition to these typical forms end-scrapers and borers are also found, which show a similar excellence of workmanship. Lance heads and other weapons and tools of bone have been found sparingly in the Solutréen. Bone needles with an eye-hole, similar to those found so abundantly in the succeeding Magdalénien, also occur, but not in any great numbers. Little is known about the art of this period, but a few drawings of animals have been found in Solutréen strata, and these seem quite up to the level of Aurignacien art. The outstanding feature of the Solutréen is, however, the technical skill attained in the fashioning of stone implements. This high-water mark of perfection does not appear to have been reached in all parts of Europe. It was largely confined to France and Northern Spain, but has also been proved in Moravia, Russian-Poland and Lower Austria.

Tanged and shouldered points.

Bone implements.

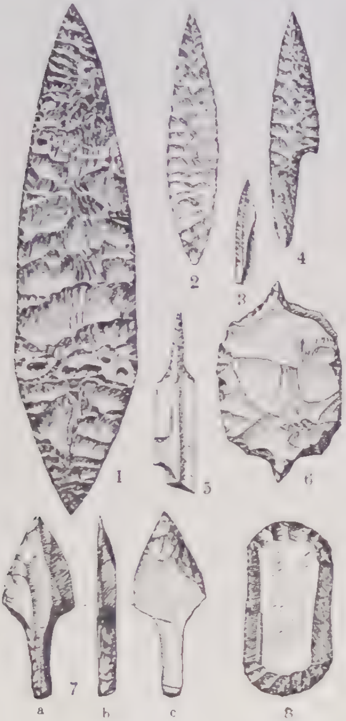

Fig. 92.—Solutréen flint implements. (From Sollas's *Ancient Hunters*. No. 7 after Bardon and Bouyssonie, the rest after G. and A. de Mortillet.)

(1) Laurel leaf point, from Volgu, Rigny sur Arroux, Saône-et-Loire ($\times \frac{2}{9}$). (2) Willow-leaf point ($\times \frac{4}{9}$). (3) Small, pointed flake ($\times \frac{4}{9}$). (4) Shouldered point, Grotte d'Eglise, Dordogne ($\times \frac{4}{9}$). (5 and 6) Borers, Grotte d'Eglise ($\times \frac{1}{3}$). (7) Tanged arrow-head, La Font-Robert, Corrèze ($\times \frac{4}{9}$). (8) Double scraper, Grotte d'Eglise.

Magdalénien

Magdalénien stone-work.

The Magdalénien is the last stage of the Palaeolithic Period. The stone-work which characterises it, however, shows a distinct falling off from the high level of excellence displayed in the preceding Solutréen. The instruments are mostly elongated flakes, and are generally of small size. The retouching is of the simplest nature, and, where present, is confined to the margins of the flakes. Among the commonest forms are blades, scrapers, gravers and boring tools. The beautiful laurel-leaf point of the Solutréen has entirely disappeared, and such implements as occur are not characteristic in any way except through their general simplicity. This

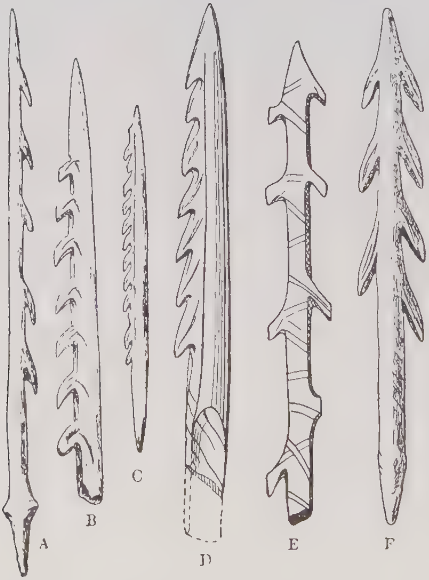

Fig. 93.—Barbed harpoons from the Middle (A, B, C, D) and Upper (E, F) Magdalénien stages. (The whole figure reduced from Sollas's *Ancient Hunters.*)

A, from the Grotte du Roc du Courbet, Bruniquel (after Cartailhac, $\times\frac{4}{9}$). B, from San Marcel (after Breuil, $\times\frac{4}{9}$). C, from Bruniquel (after Cartailhac, $\times\frac{4}{9}$). D, from Salpêtrière (after de Fondouce, $\times\frac{4}{15}$). E, from the Kesslerloch, near Thayngen (after Merck, $\times\frac{4}{9}$). F, from Bruniquel (after Cartailhac, $\times\frac{4}{9}$).

Increasing use of bone and horn.

decadence of the stone industry was due, no doubt, to the increasing use of bone and horn, the working of which was brought to a high degree of perfection by the Magdaléniens. From these materials were manufactured all sorts of implements, from needles, awls and fishing-hooks to spear and harpoon points. The latter show a progressive development throughout the period. In the earlier stages the harpoon points are simple and unbarbed, in the middle stages they possess a single row of barbs along one side, and in the upper stages two rows of barbs, one at each side.[1] (Fig. 93).

Drawing and engraving.

The drawing and engraving of the Magdalénien men show on the whole an advance on that of the Aurignaciens. Some of the drawings are even strikingly artistic, as for example the famous grazing reindeer from the Kesslerloch (Fig. 85). Bone and horn implements of all sorts are repeatedly decorated with engravings of animals, and this character helps to distinguish them from the earlier and ruder Aurignacien bone-work. Carving in the solid was also brought to a high decree of perfection during the Magdalénien Period, and remarkable artistic skill is shown in the adaptation of the figures of animals to certain designs. A striking example is shown in Fig. 94. In the representation by sculpture of the human form, however, the Magdalénien art is distinctly inferior to that of the Aurignacien. Such carved female figures as occur are as conventional as any penny doll, and unlike those of the Aurignacien, give no conception of the racial characters of the people who fashioned them.

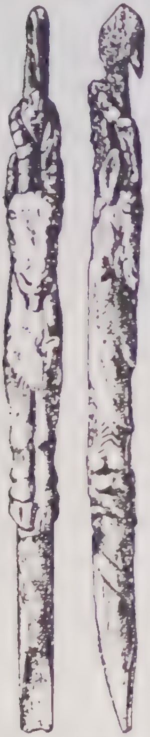

Fig. 94. Throwing stick in ivory from the Magdalénien of Mas d'Azil. (× ½. From Sollas's *Ancient Hunters*, after Piette.)

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[1] Sollas, *Ancient Hunters*, p. 312.

Correlation with change of climate.

We have now passed in review the leading characters of the various stages of the Palaeolithic Period, and, having obtained this ground-work, we are in a position to discuss various points of general interest. The most essential point for the student of glacial geology is to enquire to what extent these stages can be correlated with the changes of climate which affected the Quaternary Period. Of the various lines of evidence bearing on this question one of the most obvious is the nature of the stations or dwelling-places of the different periods. Another line of evidence is that derived from the faunas associated with the implements. These two aspects of the subject we shall now briefly discuss.

Fauna of the Chelléen.

The fauna of the Chelléen most distinctly indicates a warm climate. The leading forms are *Elephas antiquus*, *Rhinoceros merckii*, and hippopotamus. The two first named species are allied to the Indian elephant and Indian rhinoceros, and have been found in the interglacial deposits of Switzerland, such as the "Schieferkohlen" and the calcareous tufa of Flurlingen near Schaffhausen.[1] *Elephas primigenius* and *Rhinoceros tichorhinus*, which by their thick covering of wool were adapted to a colder climate, are entirely absent. The Chelléen implements are found mainly in river gravels, and from this fact and from the character of the fauna we may conclude that the climate was sufficiently genial for man to live in the open.

Fauna of the Acheuléen.

The fauna of the Acheuléen indicates a transition to colder conditions. *Rhinoceros merckii* and hippopotamus have disappeared, and although *Elephas antiquus* persists it is much rarer than in the Chelléen. On the other hand the cold-loving forms, *Elephas primigenius* and *Rhinoceros tichorhinus*, make their appearance.[2]

The two faunas of the Moustérien.

The Moustérien presents a more difficult problem, since it is found associated with both cold and warm faunas. The cold fauna, comprising *Elephas primigenius* and *Rhinoceros tichorhinus*, is, however, by far the most frequent. If any faith is to be placed in its repeated occurrence we must regard the Moustérien as contemporaneous with an ice age. There are, however, Moustérien stations which we cannot regard as in any sense glacial. In the Grimaldi Grotto, near Mentone, there is at the top a glacial fauna, and beneath this a Moustérien horizon with *Elephas antiquus*, *Rhinoceros merckii*, and hippopotamus.[1] At Taubach, near Weimar in Germany, there is a calcareous tufa lying on the drift of the northern glaciation, and in turn overlain by loess. This contains Moustérien implements and a warm fauna including *Elephas antiquus* and *Rhinoceros merckii*. These two cases seem to show that we must regard the Moustérien as in part contemporaneous with an interglacial period. Several facts seem to indicate that this warmer portion of the Moustérien succeeded the colder portion. In the preceding Acheuléen we already have clear indications of the approach of cold conditions, and this precludes us from regarding the warm period of the Moustérien as a continuation of that of the Chelléen. Moreover, the drift beneath the station of Taubach proves a greater extension of the ice prior to the warm period. Finally we find, in the Grimaldi Grotto, a glacial fauna again succeeding this warm fauna. All this evidence tends to show that the Moustérien was not only contemporaneous with the glacial period which followed upon the genial Chelléen, but also extended into the succeeding interglacial period.[2] This conclusion is borne out by the nature of the stations, most of which are found in caves, but some also in the open air in river deposits.

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[1] Penck, *Die Alpen im Eiszeitalter*, pp. 581 and 421.

[2] Déchelette, *Manuel d'archéologie*, vol. i. p. 83.

Nature of the Younger Palaeolithic stations.

We now come to the Younger Palaeolithic Period, the earlier phases of which appear to have been characterised by a marked steppe climate, and the later phases by a recurrence of glacial conditions. In the east of Europe the Younger Palaeolithic stations fall, according to Hoernes, into two classes :—

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[1] Penck, *Die Alpen im Eiszeitalter*, p. 744.

[2] *Ibid.* p. 744, etc.; "Das Alter des Menschengeschlechtes," *Zeitschrift für Ethnologie für 1908*, p. 390.

(1) Those in the loess and loess-like deposits.
(2) Those in the caves and shelters.

The stations of the first class are exclusively Aurignacien and Solutréen, those of the second for the most part Magdalénien. In the west the conditions are somewhat similar, for the Magdalénien discoveries are almost entirely confined to caves. The Aurignacien and Solutréen implements occur not only in the caves, but also far out on the adjoining slopes, and many of the stations have merely a sheltering rock wall or are entirely in the open. We may therefore safely conclude that the climate of the Aurignacien and Solutréen was at least dry and possibly not very cold. The Magdalénien, on the other hand, was accompanied by a climate of great severity.

Aurignacien fauna.

These conclusions are borne out by the study of the faunas of the three periods. The fauna of the Aurignacien is especially characterised by the abundance of the horse. It includes also *Elephas primigenius*, *Rhinoceros tichorhinus*, *Ursus spelaeus*, *Felis spelaea*, *Hyaena spelaea*, *Bison priscus*, *Cervus megaceros*, *Cervus elaphus*, *Cervus tarandus*, *Cervus capreolus* and *Capra ibex*.[1] This coincides fairly well with the fauna of the loess, and it is worthy of note that, in the loess-like deposits of Thiede, Nehring found, in association with the steppe fauna, a few implements of Aurignacien type. The fauna of the Solutréen is very similar, but the reindeer is more abundant, an increasing severity of climate being thus indicated.

Magdalénien fauna.

The Magdalénien is everywhere found in association with a thoroughly arctic fauna, the outstanding feature of which is the abundance of the reindeer. This fauna includes the horse, bison, wild ass, saiga antelope, Canadian deer, musk-ox, lemming arctic fox, arctic hare, piping hare, glutton, grizzly bear, etc. The mammoth occurs rarely; the woolly rhinoceros is almost, if not entirely, extinct.[2]

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[1] Joseph Déchelette, *Manuel d'archéologie*, vol. i. p. 127 (1910).
[2] *Ibid.* vol. i. p. 149 (1910); Sollas, *Ancient Hunters*, p. 348 (1911).

Direct correlation with the northern glaciation.

By far the most important class of evidence as regards the question of correlation is that afforded by those Palaeolithic stations which lie actually on the moraine of the Quaternary ice-sheet, or are in some manner definitely dated with regard to it. Unfortunately, however, the known cases where such direct relations can be observed are very few. The great majority of the Palaeolithic stations are far removed from the glaciated areas. Some, however, occur close up to the margin of the glaciation, and others actually within it. Among the latter is the famous deposit of Hoxne[1] in Southern England, discovered by John Frere in 1797, and subsequently investigated by Prestwich, and later still by Clement Reid. Here in a hollow in the Chalky Boulder-clay, and clearly overlying it, are some lacustrine beds, which are in turn overlain by sand and loam with Acheuléen *coups-de-poing*. Moreover, Clement Reid's investigation of the fossil flora of the lacustrine deposits shows a most interesting oscillation of climate between the period of the Chalky Boulder-clay and the Acheuléen sands. The section shows the following succession:—

Hoxne.

Sand and loam with Acheuléen *coups-de-poing*.

Black loam with arctic plants (*Betula nana, Salix polaris*).

Lignite.

Lacustrine clay with temperate plants (*Alnus glutinosa, Rosa canina*).

Chalky Boulder-clay.

From this we see that the Acheuléen period was, at least in part, contemporaneous with or later than a cold period, which was in its turn separated from the period of the Chalky Boulder-clay by a temperate or interglacial period.

Gravels of the Ouse.

Acheuléen implements have also been discovered by Prestwich, Evans and Lyell in the gravels of the Ouse, the valley of which is cut through the Chalky

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[1] See Sollas, *Ancient Hunters*, p. 400 (1911). Clement Reid, "Report of the Committee on the Relation of Palaeolithic Man to the Glacial Epoch," *Rep. Brit. Assoc.*, 1896, pp. 400-415.

Boulder-clay.[1] It is thus abundantly clear that the Acheuléen period is later than the Chalky Boulder-clay, and the plant investigations of Clement Reid seem to show that it was separated from the glacial period, in which this drift-sheet was deposited, by an interglacial period.

The Acheuléen later than the Chalky Boulder-clay.

The warm Moustérien of Taubach.

On the Continent the section at Taubach near Weimar, referred to above, shows that the Moustérien was contemporaneous with a warm period, which was later than the greatest extension of the ice in that part of Germany.

The Aurignacien loess.

Again, the loess of Westeregeln and Thiede, the fauna of which has been described above, overlies deposits with an arctic or tundra fauna. At Thiede, as we have just pointed out, a few implements of Aurignacien type were found in the loess. From this we may conclude, as is also evident from other considerations, that the Aurignacien steppe period succeeded a glacial period.

Correlation with the Alpine glaciation. Moustérien.

Somewhat better evidence is available in the case of the Alpine and Pyrenean glaciers. Thus, in the Saône district, the Moustérien stations with arcto-alpine fauna and the area of the Riss Glaciation are mutually exclusive. The stations never occur on the moraine of this glaciation or within the region covered by it. The Würm Glaciation in the Saône district is far less extensive than the Riss Glaciation, and has an area rich in caves just outside its limits. From this it is evident that the arctic Moustérien period was at least as old as the Riss Glaciation. Penck regards the arctic Moustérien as equivalent to the Riss Glaciation, and the temperate Moustérien as extending into the succeeding Riss-Würm Interglacial Period.[2]

Pyrenees.

The investigations of Obermaier in the Pyrenees afford grounds for the ranking of the Acheuléen in the glacial chronology. Penck has brought Obermaier's facts into conformity with his reading of the Alps, and shown that here, as in the Alps, there are four fluvio-glacial gravel terraces as well as an older Pliocene gravel on the plateaus, thus :

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[1] Sollas, *Ancient Hunters*, p. 349 (1911).

[2] Albrecht Penck, "Das Alter des Menschengeschlechtes," *Zeitschrift für Ethnologie für 1908*, p. 390.

Gravel of the plateaus . . .	Pliocene.
Older Deckenschotter . . .	Günz Ice Age.
Younger ,, . . .	Mindel ,,
Higher terrace gravel . . .	Riss ,,
Lower ,, ,, . . .	Würm ,,

According to Penck, the last mentioned terrace, into which the Garonne cuts to a depth of 20 m. above Toulouse, can be traced up to the end-moraine of Montrejean, where it ends. It is therefore fluvio-glacial, and not alluvial as Obermaier thought. Harle has found remains of the *Primigenius* fauna in it.

Acheuléen implements have been found at Fonsorbes, west of Toulouse, on the Younger Deckenschotter of the above series, and they do not encroach on the immediately neighbouring High Terrace Gravel. They are therefore younger than the Mindel Ice Age and older than the Riss Ice Age, and thus to be referred to the Mindel-Riss Interglacial Period. As Acheuléen implements are, however, generally found in association with a mixed or an arcto-alpine fauna, it is probable that the Acheuléen extends into the Riss Ice Age. The immediately preceding Chelléen, with its temperate climate, must be regarded as being embraced within the Mindel-Riss Interglacial Period.[1]

Magdalénien stations later than the Würm Glaciation.

Somewhat better evidence is available in the case of the Magdalénien Period. On the north-western side of the Alps three Palaeolithic stations are known which are very definitely later than the Würm Glaciation.

At Schussenried, in a trough-like hollow in the outer portion of the Young End-moraine, O. Fraas found Palaeolithic implements which were identified by de Mortillet as Magdalénien.

In the Kesslerloch, near Thayngen, Merck and others found numerous Palaeolithic implements, which, according to de Mortillet, were also typical Magdalénien. This cave opens into one of the numerous outflow channels cut by the waters of the Würm Glaciation, and lies within the region covered by the Young End-moraine.

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[1] Penck, *ibid.*

The Schweizersbild, near Schaffhausen, lies also in an outflow channel of the Würm Glaciation. The lower beds are, according to de Mortillet, typical Magdalénien; the upper appear to be Neolithic or, perhaps, Tourassien.

The fauna of these three Magdalénien stations shows a remarkable mixture of high alpine species with arctic and subarctic continental forms. The following is a list:—

- High Alpine—
  - Wild Goat (*Capra ibex*).
  - Marmot (*Arctomys marmotta*).
  - Chamois (*Capella rupicapra*).
- Arctic—
  - Reindeer (*Rangifer tarandus*).
  - Glutton (*Gulo borealis*).
  - Ice Fox (*Vulpes lagopus*).
  - Musk Ox (*Ovibos moschatus*).
  - Banded Lemming (*Myodes torquatus*).
  - Ptarmigan (*Lagopus alpinus*).
  - Swan (*Cygnus musicus*).
- Continental (Steppe-dwellers)—
  - Horse (*Equus caballus*).
  - Wild Ass (*Equus hemionis*), proved by drawings.
  - Bison (*Bison priscus*).
  - Steppe marmot (*Cricetus phoeus*).
  - Siberian Social Mouse (*Arvicola gregalis*).
  - Pika or Tailless Hare (*Lagomys pusillus*).
- Extinct—
  - Woolly Rhinoceros (*Rhinoceros tichorhinus*).
  - Mammoth (*Elephas primigenius*).
- Beasts of prey—
  - Wolf, fox, brown bear, lion.

We have given this fauna in full because of the definiteness with which it is dated. Penck points out that the various apparently discordant elements of which it is composed are not necessarily irreconcilable with one another; a climate such as exists in lat. 50°-55° N. in the east of European Russia would suit all the animals. The beasts of prey mentioned at the end of the list have no significance, since their presence is conditioned by the abundance of food, and not in any way by the climatic conditions.

Penck also calls attention to the presence in these stations of fragments of the wood of coniferous and deciduous trees (probably beech). They indicate that the station was below the tree limit, and if so the snow-line must have lain at least 300 m. higher than during the maximum of the Würm Ice Age.[1]

Relation to the retreat-stadia.

These stations prove that the Magdalénien is distinctly post-glacial as regards the maximum of the Würm Ice Age. Its arcto-alpine fauna shows, however, that the climate throughout the period was highly glacial. Penck has brought forward evidence, in connexion with the higher terrace of Lake Constance, which tends to show that the Magdalénien fauna occupied the country during the Bühlstadium, and that man was contemporaneous with this fauna. The Magdalénien, however, does not appear to have outlived the Geschnitzstadium, and as the Neolithic deposits show no sign of any climatic oscillation equivalent either to this or the succeeding Daunstadium, they must clearly be later than the latter. These two stadia and the intervening inter-stadial period thus represent the interval between the Magdalénien and Neolithic Periods.

The Palaeolithic races.

The actual fossil remains of Palaeolithic man are exceedingly rare, but sufficient is now known to show that at different stages of the Palaeolithic Period western Europe was occupied by no less than three distinct races, each with its peculiar type of skull. These types of skull are known respectively as the Neandertal-Spy type, the Grimaldi type, and the Crô-Magnon type. Curiously enough they appear to correspond with certain of the stages of culture above described, thus:

Moustérien . . .	Neandertal-Spy Race.
Aurignacio-Solutréen . .	Grimaldi Race.
Magdalénien . . .	Crô-Magnon Race.

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[1] Penck, *Die Alpen im Eiszeitalter*, pp. 422-426.

The Neandertal-Spy Race.

The Neandertal-Spy Race was characterised by a peculiarly massive type of skull of considerable capacity, exceedingly prominent superciliary ridges and a receding forehead. The original Neandertal skull was found in a cave near Düsseldorf in 1857. It was only a fragment, but showed all these characters very markedly. Two skeletons of this race of men were, however, discovered in the celebrated Grotto of Spy in Belgium. They were found in the lowest stratum in front of the cave, in association with numerous Moustérien implements. This stratum was overlain by beds with Solutréen implements, abundant remains of mammoth, several hearths, statuettes clearly referable to the earlier part of the Newer Palaeolithic, and an enormous mass of ivory fragments—debris from the carving.

In addition to these type specimens some teeth have also been found in the Moustérien strata of Taubach. In the Chelléo-Moustérien strata of the cave of Sipka, near Stramberg in Moravia, a fragment of a very massive lower jaw was discovered. It had a receding chin, and the character of the teeth indicated that it belonged to a child of eight or ten, although the massiveness was that of a well-grown man. One of the most interesting finds, however, is that of Krapina in Kroatia. In the lower or Chelléo-Moustérien strata there occurred fragments of human bones and teeth, referable to no less than ten individuals of different ages, and exhibiting in a very marked way the characters of the Spy-Neandertal race, such as great strength of jaw, receding chin, and prominence of the brow-ridges, also a remarkable development of the folding of the enamel of the teeth. The prominence of the superciliary ridges is even greater than in the Spy and Neandertal skulls. It is especially marked in young individuals, being in that case even more pronounced than in the famous Pliocene *Pithecanthropus erectus* found by Dubois in Java. The numerous milk and permanent teeth show characters of especial interest. The former are exactly like those of Taubach, while the latter show peculiar folds and wrinkles of the enamel of a pithecoid nature, such as do not occur in recent man.

The Grimaldi Race.

The Grimaldi Race is known to us through the discovery of two skeletons in the Aurignacien strata of the Grotte des Enfants near Mentone. These belonged to an old woman and a boy, whose bodies had been merely laid on the floor of the cave and surrounded with stones. The subsequently deposited strata had a thickness of 10 metres. Both skeletons show distinctly negroid characters. The skulls are long or dolichocephalic, the eyebrow ridges have only a slight prominence, the nose is flat with nasal gutters at the base, the jaws prominent or prognathous, the chin slightly retreating, the palate parabolic in outline and the teeth large. Among the living races they approximate most nearly to the Bushmen of Africa, though in some respects they also resemble the aborigines of Australia. That they probably represent the dominant race in Aurignacien times is indicated by the widespread occurrence of female statuettes in the Aurignacien stations. These, as has been mentioned above, show negroid characters of sufficient distinctness to justify the conclusion that the Grimaldi race was by no means confined to the neighbourhood of Mentone, but had a much wider distribution throughout Europe.

The Crô-Magnon Race.

In point of physical development the Crô-Magnon race is in marked contrast to the forms found in the lower horizons, standing high above them in point of development. It is, in fact, a very advanced type showing close relationship to certain living races of the present day. The skull is long, or, as it is called, dolichocephalic, and the face orthognathous, *i.e.* without any great protuberance of the jaws. The chin is prominent and the forehead high, without any marked development of the brow-ridges. Skeletons or skulls have been found in Magdalénien strata in the shelter of Crô-Magnon, Laugerie-basse, La Chancelade, the cave of Duruthy near Sorde, the seventh bed of the Grotte des Enfants near Mentone, and in Fürst-Johann's Cave near Lautsch in Moravia.

It is very remarkable that these Magdalénien men, who lived a life in most respects very similar to that of the Eskimo of the present day, were almost identical with them in anatomical structure. So marked is this resemblance, and so marked also is the correspondence in other respects, such as industry and art, that it has even been suggested that the modern Eskimos are the direct descendants of the Magdalénien reindeer-hunters.

The question of discontinuity.

This fact of the existence of three distinct races in the Palaeolithic Period raises the question as to whether there is really any genetic connexion between the Moustérien, Aurignacio-Solutréen and Magdalénien industries. One would naturally be led to expect a considerable break with each change of race. When considered from this point of view, however, the implements and works of art do not seem to bear out the idea. There is really no marked distinction between the Moustérien and early Aurignacien stone-work. The Aurignacien work was certainly more skilfully done than the Moustérien, but it introduced no new idea. The bay-leaf point and tanged point, which show a marked advance, do not appear, at least abundantly, until late on in the Solutréen. De Mortillet considered the bay-leaf point to have been developed from the Moustérien point, which had secondary flaking on one side only, by the extension of the flaking on to the other side also. It is much more likely, however, as Hoernes points out, that it is merely a highly perfected Acheuléen *coup-de-poing*. The tanged point, on the contrary, introduces a new idea, namely, the use of a barb, but, as has been repeatedly pointed out above, this is a late product of the Solutréen, and does not appear to have arrived with the Grimaldi race of men.

In the case of the Aurignacio-Solutréen and Magdalénien industries the transition appears to be even more gradual. The statuettes are clearly a product of the Grimaldi race, as is shown by the peculiar form of the female figures. Yet these are found in the same deposits as the earlier etchings, and the art of etching is continued into and reaches its highest development in the Magdalénien. If there is a break in the Younger Palaeolithic Period, it is really impossible to say where it should be placed. Perhaps, however, the gradual passage is not so hard to understand, when we consider how little effect the invasions and conquests of historic times have had on the manner of life of the conquered nations.

Palaeolithic man in England.

Before leaving the subject of Palaeolithic Man it will be well to consider briefly certain facts bearing on his presence in England. The following is a list of the principal localities in which implements and other remains of the different stages have been discovered:—

Chelléo-Moustérien.
  Alluvium of the Thames, Ouse, and Avon; Brixham Caves and Wookey Hole, in Somersetshire; Kent's Hole, near Torquay in Devonshire; Robin Hood's Cave, near Creswell in Derbyshire.
Solutréen.
  Robin Hood's Cave and Church Hole near Creswell; Kent's Hole.
Magdalénien.
  Robin Hood's Cave, Church Hole, and Kent's Hole.

It is pretty generally recognised that the Palaeolithic river gravels of the Thames, Ouse, and Avon are to be referred to the same period as those of the Somme and Seine. They have the same stratigraphical relations, the same flint implements, and the same peculiar fauna, including *Elephas antiquus*, *E. primigenius*, *Rhinoceros merckii*, *R. tichorhinus* and hippopotamus. The typical instrument is the *coup-de-poing*. This is also found in the caves, where, however, it is associated with Moustérien types. In Kent's Hole the Moustérien was a bone breccia with abundant remains of mammoth, woolly rhinoceros and wild horse.

The Solutréen and Magdalénien remains are confined to the caves. The Magdalénien is not well represented. A few animal drawings, found in a cave near Creswell, are all that we have to represent the art of the period.

Nevertheless the relics found are so characteristic, that it is necessary to assume a connexion between England and France as late as the Magdalénien. Whether this connexion was continuous throughout the Palaeolithic Period it is impossible to say. The Straits of Dover may not have been cut until then, but, on the other hand, the connexion may have been only an intermittent one due to changes of sea-level.

The remains of Palaeolithic man in the British Isles are completely confined to central and southern England. No trace of his presence has been detected either in Ireland, Scotland, or the north of England. These are the districts covered by the newer drift.

In the south of England, especially on the uplands, there is found a type of very rude implement supposed to represent an earlier stage than the Palaeolithic. These implements are of the class referred to above as "eoliths." The working is so rude as to leave it open to doubt as to whether it could not be produced by natural causes. The question, being a controversial, one will not be further discussed here. It is very necessary, however, to bear in mind the fact that types of implement so rude as to indicate the very first beginnings of man's industry do appear to exist in the south of England.

The elephant-trench at Dewlish.

The contemporaneity of man with *Elephas meridionalis* appears to be established by Osmond Fisher's discovery of the elephant-trench at Dewlish, in Dorset. This was a steep-sided trench in the chalk about 100 feet long and 12 feet deep, opening out at one end on the scarp of the hill, but terminating at the other in a smooth, apse-like end. The bottom of the trench was also a smooth surface of chalk, and the whole had an obviously artificial character, there being no trace of any natural joint, fissure, or fault. It bore a close resemblance to the pitfalls constructed by the natives of Africa on the routes to the drinking places, with the object of disabling the elephants and spearing them to death in their helpless condition. The Dewlish trench contained abundant bones of *Elephas meridionalis*, embedded in dust-like sand and flint gravel. Some of the flints were said by Dr. Henry Woodward to resemble eoliths.[1]

Preglacial man in Cornwall.

A discovery made by Mr. Clement Reid in Cornwall is of importance, as it establishes the presence of man in Britain in preglacial times. At Prah Sands, about seven miles east of Penzance, is a section of the preglacial raised beach and the overlying head or rubble-drift (Chap. V). In this section, between the beach-gravel and head, there occurs a land wash composed of sandy loam or brick-earth, and traceable in the cliff for about 200 yards. It seems to be an ordinary soil washed from the cliffs above, for it is full of small chips of vein quartz. Towards the old buried cliff it becomes more stony and like the head above, from which, however, it is quite distinct in other places. It is full of small vertical roots and must at one time have been a true land surface.

Towards the top of the loam occurs a black seam about six inches thick, full of fragments of charcoal mixed with small splinters of carbonised bone and fragments of burnt earth. The charcoal was particularly abundant at several spots where the loam contained groups of three or four blocks or flattish slabs of stone.

There being no doubt that this was a surface upon which man had made hearths and lighted fires, implements were carefully searched for, but none came to light, unless indeed some battered pieces of quartz occurring in the black loam can be regarded as such. The thorough decalcification to which the deposit had been subjected had removed all traces of uncarbonised bone.

This discovery seems to prove the presence of man in Cornwall at a period when the beach had been raised sufficiently high above sea-level to permit the accumulation of land-wash on its surface, and before the formation of the rubble-drift or head. It is necessary, however, in connexion with this discovery and the elephant-trench at Dewlish to sound a note of warning. The observations certainly rest on good authority, but they are isolated and unconfirmed. Those who have worked a good deal at geology will recognise that no single observation, by whomsoever made, can ever be regarded as an absolute demonstration until new discoveries are brought to its support.

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[1] Osmond Fisher: "On the Occurrence of *Elephas meridionalis* at Dewlish (Dorset)," *Quart. Journ. Geol. Soc.*, vol. lxi. p. 35 (1904). See also J. C. Mansel-Pleydell, *Proc. of the Dorset Natural History and Antiquarian Field-Club*, vol. x. p. 12 (1889), and vol. xiv. p. 139 (1893).

The Transition Period

Contrast between Magdalénien and Neolithic.

Over the greater part of Europe, as has been pointed out above, there appears to be a great hiatus between the Palaeolithic and Neolithic culture. Between the Magdalénien and the age of polished stone (de Mortillet's "Robenhausien") there certainly is a most complete break. No two types of industry could be more sharply contrasted with one another. We cannot emphasise this contrast better than by setting it forth in tabular form, thus :

MAGDALÉNIEN	NEOLITHIC
Poorly developed stone industry.	Highly developed stone industry, art of grinding and polishing stone.
Remarkable skill in drawing and etching.	Absolutely no pictorial art.
Hunting and fishing the only occupations.	Agriculture and the keeping of domestic animals.
A cold fauna with reindeer and mammoth.	The fauna of the present day.

There are found, however, in various parts of Europe certain phases of industry which precede the Neolithic proper, and thus in some degree serve to fill up this gap. They are far, however, from affording a proper link either with the Magdalénien or any other phase of Palaeolithic culture. These phases are known by the following names :

a. Campignien.
b. Tardenoisien.
c. Asylien (Tourassien of de Mortillet) and Arisien.

The Campignien industry is by far the most widely distributed of these phases of culture and also the best understood. It is found not only in France, Italy, and Denmark where it is best known, but also in Norway, the British Isles, Belgium, Finland, and other parts of Europe. The name comes from Campigny in France, where these implements were first discovered. The most instructive find is that of d'Ault du Mesnil in the Somme basin. Here, over the gravels of Chelléo-Acheuléen age, there occurred a loess with younger but still purely Palaeolithic remains, and over this a loam with the Campignien implements. These contained two types quite distinct from any Palaeolithic implements known, namely, the cleaver (French *grand-tranchet*, Danish *skivespalter*) and the rough hewn hammer or axe-head. Examples from the type locality are shown in Fig. 95. Towards the upper portion of the loam this industry became finer, and polishing appeared on the edges or over the whole implement, and a passage was thus proved from these rough-hewn implements to the polished Neolithic axe-head.

The Campignien.

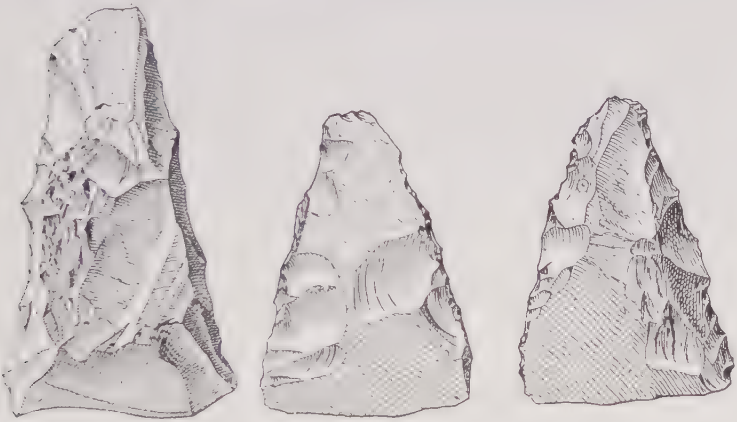

FIG. 95.—Flint cleavers found at Campigny, Seine-Inférieure. (After Déchelette.)

Characteristic implements.

Gradual transition to Neolithic types.

These two types of instrument, the rough-hewn axe-head and the *skivespalter*, are peculiarly characteristic of the Danish *kjökkenmöddingar* or rubbish-heaps, that are ranged along the shore-lines belonging to the maximum of the Littorina-Tapes submergence. They are there, as in France, the forerunners of the Neolithic industry proper. Similar implements occur along the highest shore-line in the Kristiania district, where they have been studied by Brögger, the only difference being that they are not made of flint but of other kinds of fine-grained stone. The rough-hewn axe-head is Brögger's "Nöstvet type," and here, as in France, it passes gradually into the Neolithic type by the addition of polishing along the cutting edge. These implements can be traced south from Denmark along the coast of the North Sea into Belgium and through France to Italy, this appearing to be the route along which the people who brought the industry migrated northward. It would seem as if the earlier Neolithic races spread over Europe before they had discovered the art of polishing stone. At this period also they were a hunting and fishing folk, and had not yet acquired any agricultural or pastoral habits.

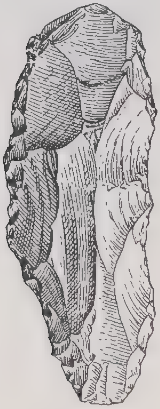
Fig. 96.—Rough-hewn axe-head or pick found at Campigny. (After Déchelette.)

Absence of connexion with the Palaeolithic.

Although unquestionably pre-Neolithic, it is doubtful if the Campignien industry affords any connexion with the Palaeolithic Period. It is never associated with, and is quite distinct in every way from, the Magdalénien. It is only in Italy, where the Magdalénien is absent, that any appearance of a passage presents itself. Here a stone industry, describable either as Solutréen or advanced Acheuléen, persisted down to the end of the Palaeolithic Period, and the peculiar Campignien implements are found in association with the Solutréen types, including the tanged point and the bay-leaf point. As these Solutréen types were manufactured in Europe throughout the Neolithic Period, this is, however, really no demonstration of a passage.

The Tardenoisien.

The Tardenoisien industry embraces a very widely distributed class of extremely small geometrically shaped flint implements, with sharp cutting edges or very delicate secondary flaking. In the rare cases where they are seen in relation to Neolithic implements proper they occur beneath them. They are mostly found, however, in distinct localities. Their use is still a matter of speculation. The occurrence of these types in the Danish *kjökkenmöddingar* connects them pretty definitely with the Campignien.

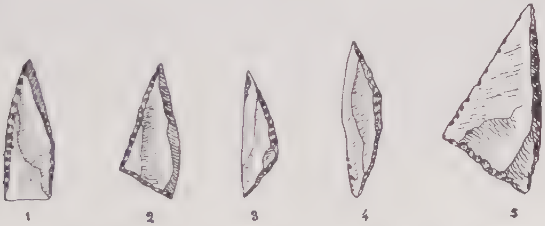

Fig. 97.—Tardenoisien implements from Hédouville, Seine-et-Oise. (After Déchelette.)

The Asylien.

The most extraordinary of all the supposed transition phenomena is Piette's Asylien. It is based on the stratigraphy of the cave Mas d'Azil in Southern France. This cave contained a whole series of Palaeolithic strata culminating in the deposits of the Reindeer Period (Magdalénien). Thereon followed the famous "Assise à galets coloriés," the industry of which is the most extraordinary puzzle that archaeological researches have ever brought to light. The bed contained a quantity of stones on which are painted points and straight lines, separate or repeated up to the number of eight, broken lines, circles, crosses, circles partitioned by a cross, and so on, and in addition to these some figures the similarity of which to modern capital letters was so great, that Piette was forced to the otherwise untenable idea that

The painted pebbles.

this was one of the sources of the Phoenician script. The associated stone industry was of a type that might be either Magdalénien or Neolithic, consisting merely of small knives and scrapers. There was no trace of polished stone and no pottery. The Asylien harpoon. The horn harpoons are somewhat different from those of the Magdalénien, being flat and made of the horn of the red deer, while those of the Magdalénien have a round axis or shaft, and are made of reindeer-horn. Fauna. As regards the fauna, there is no trace either of the reindeer or the domestic animals of the Neolithic. The following animals appear to have been hunted: red deer, roe-deer, goat, urox, horse, brown bear, pig, hare, fox, wolf, and lynx. A little heap of wheat grains was found in one place, and also remains of edible fruits, Climate. indicating a climate which must have been a considerable improvement on that of the Magdalénien. There is a suggestion of a slight link with Art. the Magdalénien in the rare occurrence of drawings. These were not found in Mas d'Azil, but in the Asylien strata of the Abri Dufaure was found a piece of stone

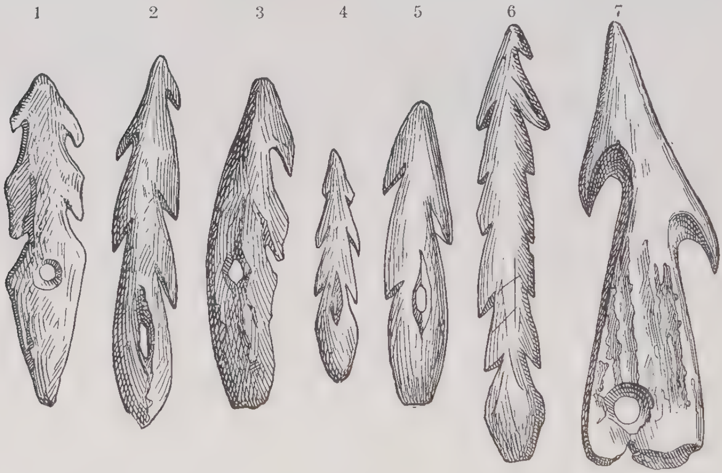

Fig. 98.—Asylien harpoons of stag-horn. (After Déchelette.)

1, 2, 3. From Mas d'Azil. 4. From the Grotte de la Tourasse (Haute Garonne). 5, 6. Grotte de Reilhac. 7. Neolithic harpoon from the Lake of Bienne, for comparison.

on which was engraved the head of a horse. Finally, the discovery in Mas d'Azil, in the beds of this period, of two skeletons showing a peculiar burial ritual, in which the flesh was scraped off the bones and the latter coloured red with ochre, provides a feature quite distinct from anything known from the Magdalénien.

Burial ritual.

In Mas d'Azil the Asylien strata were overlain by beds which Piette has named the "Étage coquillier" or Arisien. The people of this stage apparently lived largely on snails and wild fruits. Their flint implements were the same knives and scrapers as are found in the underlying Asylien, but in addition there were a number of flat slabs of flint and slate, polished off at one side or at the end to a sort of cutting edge. These Piette regards as foreshadowing the polished stone implements of the Neolithic Period.

The Arisien.

Finally, the Arisien strata were overlain in Mas d'Azil by beds of distinctly Neolithic age (Robenhausian) containing polished axe-heads and pottery, with which, however, were associated more of the Arisien type of bevelled slate and flint slabs.

Piette's Asylien is the obvious equivalent of de Mortillet's Tourassien Stage, founded on the shelter of La Tourasse near Saint Martory (Haute-Garonne). It is not, however, so well characterised in this locality as at Mas d'Azil. The Asylien or Tourassien is quite unknown except in the south of France.[1]

It must be admitted that the net result of all these investigations is a complete failure to demonstrate anything in the nature of a passage between the Palaeolithic and Neolithic industries of Europe. There is no proper mingling of any of the supposed transitional remains with undoubted Palaeolithic relics, and no sign of a gradual change. Immediate superposition counts for nothing in limiting the lapse of time between two successive industries. This is clearly shown by the fact that in some caves the Magdalénien strata still form the upper surface.

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[1] Elongated stones, ground to a cutting edge at one end quite similar to those of the Arisien of the south of France, have been found in a shell mound in the island of Oronsay off the west coast of Scotland; and not far away on the mainland of Argyll, near Oban, there is a cave which has yielded flat harpoon heads of typical Asylien shape. As no connecting links have, however, been found in other parts of the British Isles or in the north of France, it does not seem safe at present to correlate these implements with those of the south of France.

The Neolithic Period

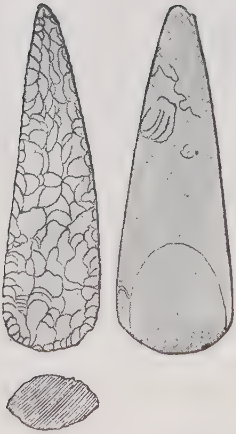

Fig. 99.—Typical axe-heads of Stage I. of Montelius' classification of the Neolithic Period. (This and the three succeeding figures after Hoernes.)

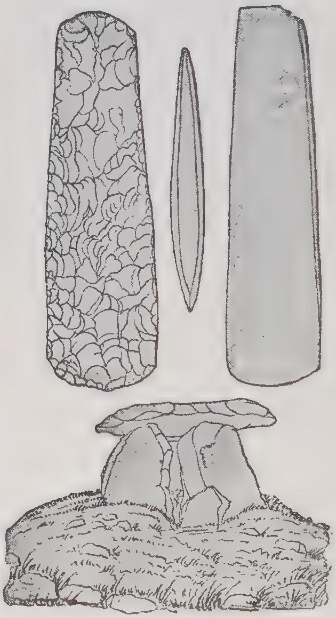

Fig. 100.—Typical axe-heads and dolmen of Stage II. of Montelius' classification.

The classification of Montelius.

Throughout the greater part of Europe efforts at the subdivision of the Neolithic Period have not been attended with any success. In Sweden and Norway, however, the classification of Montelius has been shown to have a distinct chronological value (see p. 356). It is founded on the variations in form shown by the chipped and polished axe-heads. Besides the Campignien four other sub-periods have been distinguished which belong properly to the age of polished stone; these are in order of time:

Stage I.—Axes of the point-necked type, either rough-hewn or polished, triangular in form and lenticular in cross section (Fig. 99). Mode of sepulture not known.

Stage II.—Axes of the small or thin-necked type, almost rectangular in form and with strongly arched sides and squared angles (Fig. 100). Period of dolmens.

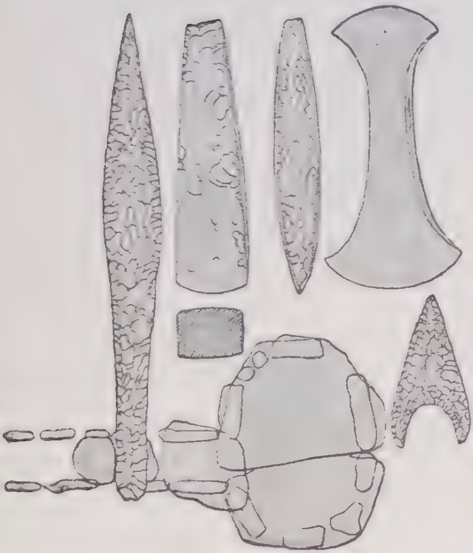

Fig. 101.—Typical axe-heads, dagger, arrow-head, and grave of Stage III. of Montelius' classification.

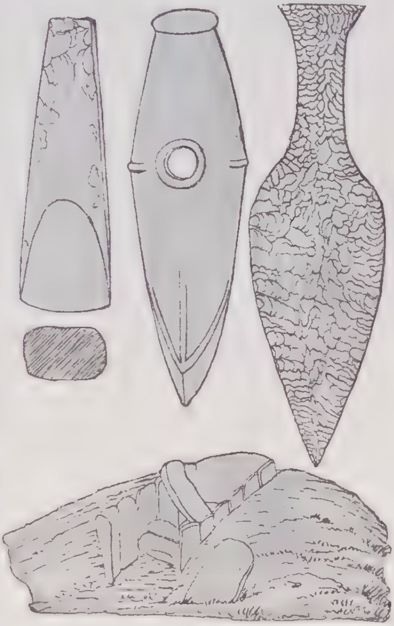

Fig. 102.—Typical axe-heads, dagger, and grave of Stage IV. of Montelius' classification.

Stage III.—Axes of the thick or broad-necked type, with relatively flat sides and nearly square cross section at about the middle (Fig. 101). Beautiful flint knives or daggers with handle (narrow-bladed type). Shaft-hole axes. Graves with covered passages.

Stage IV.—Axes as in the former period. Beautiful daggers with handle (broad-bladed type). Stone cists.[1] (Fig. 102.)

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[1] Joseph Déchelette, *Manuel d'archéologie,* vol. i. p. 334 (1910); Moritz Hoernes, *Natur und Urgeschichte des Menschen,* Bd. ii. p. 184 (1909).

Hoernes points out that the axes of stages I. and II. have a wider distribution in Northern Europe than those of the later stages III. and IV., the latter being limited to special districts. This seems to indicate that the earlier forms were modelled on imported types, while in the later stages development went on more or less locally. With the increase of pastoral and agricultural habits of life, the movement of the tribes became more restricted, and communication between the different districts less frequent. The greater security resulting from the new mode of life led locally to a high development of certain industries. Thus the art of chipping flint was, during the later stages of the Neolithic Period, brought to a high state of development in Denmark and in parts of England, *e.g.* Yorkshire. The beautiful shell-like flaking of this period, and the skill shown in fashioning implements and weapons of complex and beautiful design, proves the possession of a dexterity and knowledge far ahead of that of even Solutréen man. It is interesting to note how the introduction of metal is foreshadowed in some of the later Neolithic axe-heads which have a spread edge (see Fig. 102). These could hardly have been made except in imitation of some previously existing copper or bronze axe, either seen elsewhere or introduced by trading. It is remarkable, also, that the accompanying flint daggers seem also to be imitations of metal weapons.

The lake-dwellings of Switzerland.

The famous lake-dwellings of Switzerland belong in part to the late Neolithic and in part to the Bronze Age. The smaller dwellings near the shore and having only a short causeway are generally of Neolithic Age, while those which stand out far in the lake and have a long causeway belong to the Bronze Age.

CHAPTER XIII

THEORIES OF THE ICE AGE

General remarks—Variation of the internal heat of the earth—Variation of the intensity of solar radiation—Dubois' theory—Cold region of space—Changes in the distribution of land and water—The elevation theory—The carbonic acid theory of Arrhenius—Harmer's meteorological speculations—Obliquity of the ecliptic—Changes in the position of the earth's axis—Schiaparelli's analysis.

SUCH a remarkable departure from the relatively uniform sequence of geological evolution as is proved by the remains of the Quaternary Ice Age has inevitably led to much theorising. All possible causes of variation in temperature and precipitation—astronomical, geographical, and meteorological—have in turn been invoked to account for the fact that large areas of Europe and America were at one time covered with ice, and that the glaciers and ice-sheets in other parts of the world have formerly had a much greater extent than at the present day. Among those who have worked at the subject there is the utmost diversity of opinion as to the direction in which the solution of the problem is to be sought, and the most eminent glacialists at present reserve their judgment and are content to await further developments in our knowledge.

We shall devote the present chapter to a rapid review of such theories as are current at the present day, giving a brief account of the arguments for and against them. In the succeeding chapter we shall consider in more detail the most famous of these, the so-called Astronomical

Theory, as the main exponent of which the name of James Croll, of the Geological Survey of Scotland, will ever be famous.

Variation of the Internal Heat of the Earth.—It may be regarded as fairly certain that at an early stage of its history the earth was much hotter than at the present day, and that it gradually cooled down until life became possible on its surface. It was at one time considered by some geologists that this cooling continued throughout the geological ages and culminated in the Quaternary Glacial Period, which was held to have in this manner an easy explanation. No reason was given, however, why a return to genial conditions should have followed, and, as recent researches have proved the occurrence of Ice Ages in Cambrian and Permian times as well as in the Quaternary, we may regard this theory as entirely disposed of. The investigations of Professor Joly and the Hon. R. J. Strutt into the radio-activity of the materials of the earth's crust tend to show that a large proportion of the radiant energy given off by the earth is due to the degradation of the radio-active elements, so that it is not at all clear that the earth is becoming any cooler at present. These investigations have, however, up to the present yielded nothing in the nature of an explanation of the Glacial Period.

Cooling of the earth.

Radio-activity.

Possibility of the sun being a variable star.

Variation of the Intensity of Solar Radiation; Dubois' Theory.—A decrease in the intensity of the sun's radiation was, of course, early recognised as a possible cause of change of climate on the earth. It was, in fact, supposed that the sun might be a variable star, and that the Ice Ages occurred during its periods of "darkness." According to Sir Robert Ball, however, there is little reason to suppose that this is the case.[1] Although a certain short-period rhythmic succession in the occurrence of sunspot maxima has been proved, yet there is no indication of variation of such long period as that required for the Ice Age. Certain classes of stars, to be sure, do go through a systematic series of changes in the amount of radiation which they send to us, but it is probable that this is due to their rotation, or to the rotation around them of other bodies which intercept the light they emit.

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[1] Sir Robert Ball, *The Cause of an Ice Age*, p. 48. London, 1892.

Dubois' theory.

This question of the sun's variability has been recently discussed with considerable care by Dubois.[1] He assumes that the sun has passed through certain stages in which the conditions were such as we now see exemplified in the case of other stars. In the first stage, that of a white star, radiation was more intense. With the transition to the yellow stage there came a rapid decrease in the amount of radiation, and hence a cooling of the earth which Dubois believes to have lasted from the beginning of the Tertiary to the Pleistocene. During the yellow stage there were variations during which the sun temporarily became a red colour and the amount of radiation diminished. These periods of partial darkening are supposed to have caused the glacial periods of the Quaternary, while the intervening periods of yellow light, in one of which we now live, are the interglacial periods. This theory does not contradict any ascertained facts of astronomy or physics, but this is about the most that can be said for it. We lack as yet anything in the nature of proof that the sun actually passed through the stages postulated.[2]

Meaning of the temperature of space.

Cold Region of Space.—It has been suggested that the Ice Age may have been caused by the passage of the solar system through a colder region of space than that which it now occupies. By this it can only be meant that the radiant energy received from the stars was then less. As, however, according to Sir Robert Ball,[3] the total amount of star heat is not the ten-millionth part of that which we receive from the sun, this does not seem a very hopeful direction to look for the cause of variation in the climate of the earth. Of course, if the solar system approached or were approached by any large star, a sufficient change might be produced in this way to cause a warm epoch, but hardly an Ice Age. The close proximity of such a large body would, however, produce quite an appreciable derangement in the movements of the planetary system, and the planets, according to Sir Robert Ball, exhibit no trace of having suffered, even long prior to geological times, any great interference from outside influence.[1]

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[1] Eugen Dubois, *The Climates of the Geological Past.* London, 1895.

[2] For a criticism of Dubois' views see A. Woeikof, "Geologische Klimate," *Pet. Mitt.* vol. xli. p. 252 (1895).

[3] *The Cause of an Ice Age*, p. 54.

Changes in the Distribution of Land and Water; the Elevation Theory.—Since the days of Lyell there have always been a few geologists who incline towards the idea that the Ice Age may be explained by a change in the distribution of land and water. While it would be foolish to deny that in this way enormous changes of climate might be produced, yet it is clear that none of the main mountain ranges of Europe have come into existence or been seriously modified since Pleistocene times. The same may be said of the greater part of North America.[2] We have, therefore, to consider merely such changes as might be brought about by the retreat and advance of the sea, due either to its own rise and fall or to continental subsidence or uplift, assuming the latter to be possible. Now, it is clear from the deep excavation of the river valleys and fjords of Ireland, Scotland, and Norway, as well as Iceland and Greenland, which descend everywhere beneath sea-level, and from the continuation of the main river valleys as channels on the deeply submerged continental shelf which fringes the North Atlantic, that at some recent geological period this region stood considerably higher than at present. This elevation, which resulted in the dissection of the continental shelf, has been very generally assumed to have immediately preceded the Ice Age; and many eminent glacialists, among whom may be mentioned Warren Upham,[3] G. F. Wright, and Holst, have regarded

The fjord elevation.

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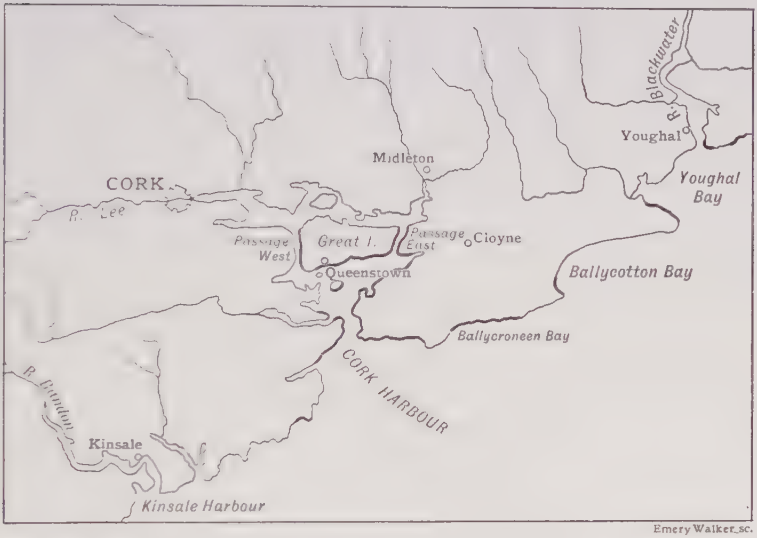
[1] *The Cause of an Ice Age*, p. 59.

[2] Pleistocene strata have been found forming the mountains around the Malaspina Glacier at a considerable altitude.

[3] Warren Upham, "The Glacial Lake Agassiz," *Mon. xxv. U.S.G.S.* p. 517 (1895). G. F. Wright, *The Ice Age in North America*, pp. 573, 584 *et seq.* New York, 1889.

Its preglacial age.

it as the immediate cause of the glaciation of Europe and North America. Now it has been quite clearly proved of recent years that this cannot be the case. The period of fjord cutting was, in fact, separated from the Glacial Period by a fairly prolonged epoch, during which the sea-level was approximately the same as at the present day. The preglacial beach, of which an account has been given in Chapter V., fringes the shores of the submerged river channels of the south of Ireland, thus showing conclusively that they had already sunk beneath the sea in preglacial times. We may, therefore, set aside the fjord uplift as a possible cause of the Ice Age. The reader will remember, however, that in the same chapter it was proved that elevation set in after the formation of the beach. It is likely that this elevation was a result rather than a cause of the glaciation, for we know that glacial conditions



Emery Walker sc.

FIG. 103.—Map of portion of the south coast of Ireland in the neighbourhood of Cork, showing the distribution of the preglacial platform of marine erosion (indicated by a black line), and the manner in which it fringes the submerged river valleys in Cork Harbour.

existed during at least the later stages of the beach, that is, before the uplift commenced.

The Theory of Arrhenius.—To Svante Arrhenius[1] we owe a theory which now has considerable vogue, namely, that which ascribes the glacial periods to a change in the amount of carbon dioxide in the atmosphere. His calculations led him to the conclusion that a decrease of from 55 to 62 per cent of the present content would produce in middle latitudes a fall of 4° or 5° centigrade, and would thus suffice to explain the temperature of the Glacial Period. He discusses the various geological processes, such as the formation of coal and limestone, and the variation in volcanic activity which might lead to changes in the amount of carbon dioxide in the atmosphere.

Variation in absorption due to carbonic acid and water vapour.

More recently Chamberlain has advanced a working hypothesis having as a basis the same idea. He takes into consideration other causes of variability in the carbon dioxide content of the atmosphere, such as the weathering of rocks and the agency of organisms. Being an extreme interglacialist, he is at great pains to show that there must necessarily be a periodicity in such changes, but it must be admitted that his arguments are somewhat forced, and that the hypothesis does not readily lend itself to the explanation of interglacial periods.

There seems, however, to be a misconception at the root of this idea of Arrhenius. Angström pointed out in 1901[2] that the theory is founded on an erroneous interpretation of observations, attributing to carbon dioxide absorption effects which are principally due to water vapour. He also proved that the earth's atmosphere contains at the present enough carbon dioxide to absorb substantially all the solar radiations which are capable of being removed by this gas, rays constituting not more than $1\frac{1}{2}$ per cent of the whole.

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[1] Svante Arrhenius, "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground," *Phil. Mag.* 5th ser. vol. xli. pp. 237-276.

[2] Knut Angström, "Über die Bedeutung des Wasserdampfes und der Kohlensäure bei der Absorption der Erdatmosphäre," *Ann. der Physik* (4), iii. p. 720 (1900). See also Hann, *Handbook of Climatology*, p. 399 (1903).

Water vapour dependent on sun-heat.

A distinct increase or decrease in the amount of water vapour in the atmosphere would undoubtedly cause great climatic modifications. The water vapour content is, however, clearly determined by the amount of radiant energy received from the sun, so that its increase or decrease cannot in any sense be regarded as an ultimate cause of such change of climate.

Redistribution of atmospheric pressure.

A similar remark applies to Mr. Harmer's[1] very ingenious speculations regarding the redistribution of the areas of high and low barometric pressure during the Ice Age. Some such redistribution undoubtedly occurred, but it must be regarded as a condition dependent on the glaciation and the altered conditions, astronomical or otherwise, which brought about the glaciation, rather than as a cause of the latter. A consideration of the meteorology of the Ice Age is, of course, essential to a proper understanding of its varied phenomena, but one may safely regard the atmosphere merely as a medium which played much the same part in the causing of the Ice Age as a musical instrument does in the production of music.

Limits of variation.

Obliquity of the Ecliptic.—We now come to a discussion of the effects of the variation of the elements of the earth's rotation and orbit. Here our reasoning rests on a somewhat sounder basis; for it is possible to calculate with considerable accuracy the change in the amount of radiant energy received by any part of the earth's surface under the altered conditions. Let us consider first the obliquity of the ecliptic. This, according to Laplace, can only vary to the extent of 1° 22·5′ on either side of the mean value 23° 28′; that is to say, that it may attain the extreme values of 22° 6′ and 24° 50′, but can never range either lower than the former or higher than the latter of these figures. It is clear that when the minimum value of 22° 6′ is attained the amount of sun-heat received at the equator is increased and that falling on higher latitudes is diminished. The reverse is the case when the obliquity attains its maximum value.

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[1] F. W. Harmer, "The Influence of Winds upon Climate during the Pleistocene Epoch," *Quart. Journ. Geol. Soc.* vol. lvii. p. 405 (1901).

Meech's calculation.

Meech has calculated the amount of heat received on each 10° of latitude at a time when the obliquity of the ecliptic was near its maximum value, 10,000 years before 1800. Comparing with the year 1850 he found the changes in the yearly heating effect due to the direct rays of the sun in the various latitudes, when expressed in thermal days,[1] to be as in the following table:—

CHANGE IN THE YEARLY HEATING OF THE EARTH AT A MAXIMUM OBLIQUITY OF THE ECLIPTIC, EXPRESSED IN THERMAL DAYS

Equator.	10°.	20°.	30°.	40°.	50°.	60°.	70°.	80°.	Pole.
−1·7	−1·6	−1·3	−1·0	−0·2	0·7	2·1	5·5	7·2	7·6

The pole, therefore, received at this period about 5 per cent more heat than at the present day, and the equator about ·5 per cent less, the middle latitudes remaining unchanged. The contrast between the seasons was also somewhat accentuated. It is considered that these figures demonstrate that no marked climatic changes can be produced in this way.[2]

Changes in the Position of the Earth's Axis.—According to the undoubted authority of Dr. Julius Hann, "the simplest and most obvious explanation of great secular changes in climate, and of the former prevalence of higher temperatures in the northern circumpolar region, would be found in the assumption that the earth's axis of rotation has not always had the same position, but that it may have changed its position as the result of geological processes, such as extended rearrangements of land and water." This assumption has up to the present, however, not been very popular with geologists as an explanation of the Ice Age, largely no doubt on account of the attitude of Lord Kelvin, who held that the apparent absence of tides in the body of the earth proved its essential rigidity, and that, therefore, no extensive displacement of the pole could occur. Quite recently, however, it has been shown that earth-tides of small amount do occur, and certain other facts seem to indicate that the rigidity cannot be as great as Kelvin supposed. Mathematical analyses dealing with the possibility of displacement of the pole in a semi-rigid earth assume in the light of these facts a new interest for geologists. The problem has been treated by Sir G. H. Darwin, who came to the conclusion that, if the earth is quite rigid, the pole can only have departed about 3° from its original position. If, however, as is probably to some extent the case, it is plastic, and thus able to adapt its form to the new rotation, then there is the possibility of a cumulative effect and the pole may have wandered 10° or 15° from its original position. It is important to note, however, that no such cumulative effect is possible with regard to the obliquity of the ecliptic, that is to say, with regard to the inclination of the earth's axis to the plane of its orbit.

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[1] The unit is the heating effect of solar radiation in a mean day at the equator, which receives 365¼ of these units during the year. The pole now receives 151·6.

[2] Hann, *Handbook of Climatology*, p. 382 (1903).

Earth-tides.

Possibility of displacement of the pole.

Schiaparelli[1] treats the problem in a more general manner, making no initial assumptions as to total or partial rigidity. He discusses three cases—

(1) That of an absolutely rigid earth.
(2) That of an earth with easily movable parts, which adapt themselves readily to the new form and distribution of stress.
(3) A third case between these two extremes, in which the earth can adapt itself to a new form, but only after the stresses due to the change have reached a certain magnitude.

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[1] "De la rotation de la Terre sous l'influence des actions géologiques," *Mémoire présenté à l'Observatoire de Poulkova à l'occasion de sa fête semiséculaire.* St. Petersburg, 1889. See also review of the above by Dr. H. Hergeselle, *Pet. Mitteil.* vol. xxxviii. p. 42 (1892).

Case of a rigid earth.

CASE 1.—If B be the maximum moment of inertia of the earth, and A the moment round any axis perpendicular to the principal axis of inertia, then the quantity $\lambda = \frac{B}{B-A}$ is fairly large and equals 305.

Now if the axis of rotation coincides with the principal axis of inertia, then the former is always at rest and coincides with the latter.

If, however, the two poles are separated, then the pole of rotation no longer maintains a constant position, but describes about the pole of inertia a circle, which it completes in $\lambda - 1$, *i.e.* 304 days. The motion has the same sign as the rotation of the earth. This is known as Euler's circle, and the time of rotation as Euler's Period.

Schiaparelli investigates first the influence which the addition or removal of a small mass has on the position of the pole of inertia. The various cases of the removal of a mass at a certain depth or the radial or superficial shifting of a mass are treated in turn.

Thus the displacement of the central plateau of Asia into the Indian Ocean (by the Indian rivers) would displace the pole of inertia about 30 km. southward along the central meridian of the plateau.

Now, when the pole of inertia moves from any cause along a meridian, the pole of rotation describes every moment a small arc of an Eulerian circle; it rolls to a certain extent in a wheel with changing spoke length. It, in fact, describes, as can be easily proved geometrically, a cycloid which, according to the initial position of each pole, can be extended or shortened. From Euler's law it follows directly that the cycloid completes each of its loops in an Eulerian Period, *i.e.* $\lambda - 1$ days, and that the "stride" of the cycloid is equal to the distance which the pole of inertia travels in an Eulerian Period. From this it also follows that, if the pole of inertia and pole of rotation originally coincided, they can never be further removed from one another than the distance which the pole of inertia travels in

$\frac{\lambda - 1}{\pi}$ days. If they did not originally coincide their distance can only be increased by about the same amount.

Taking the case of the removal of the plateau of Central Asia into the Indian Ocean and supposing it accomplished in a million years, then the pole of inertia moves 25·2 mm. in an Eulerian Period of 304 days, and this is therefore the "stride" of the cycloid described by the pole of rotation. The two poles can therefore, if originally coincident, only depart from one another to the extent of 8 mm.

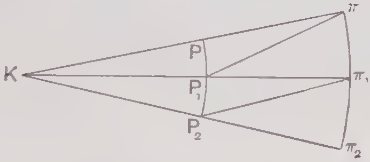

FIG. 104.—Diagram to illustrate Schiaparelli's analysis of the displacement of the pole in an earth with capacity for immediate adaptation.

The displacement of the pole of rotation is therefore mainly determined by that of the pole of inertia.

If all the geological processes at present known be taken into consideration it will be found that the displacements of the pole of inertia remain always within a limit which does not exceed a fraction of a degree, and that hence the displacement of the pole of rotation is confined within the same limits.

Earth supposed to have a capacity for immediate adaptation.

CASE 2.—The second case considered is that of an earth with a capacity for immediate adaptation, the material of which instantly yields to the smallest stresses tending to deform it, and which takes on at once, and without oscillation, a new form of equilibrium.

Let the rotation and inertia poles originally coincide at P (see Fig. 104), and suppose a small mass added at K.

Then the inertia-pole P is displaced to π along the meridian KP, and the rotation-pole P starts to describe an Eulerian circle round π, arriving at P_1 in an infinitely short interval of time, but on account of the perfect adaptability P_1 must be the new inertia-pole for the earth less the added mass. Hence the inertia-pole for the whole takes up a new position π_1 on KP_1. Similarly for P_2 and π_2. The rotation-pole and inertia-pole therefore describe circles round K.

Euler's rotation does not therefore take place in an earth of perfect adaptability to change of rotation axis. Instead there occur motions in circles whose radii depend on the position of the disturbing mass.

The relation is similarly modified when masses on the earth's surface are displaced horizontally or vertically, the Eulerian circles being replaced by curves with wide radius which can bring the pole of rotation into any position on the surface of the earth.

Let us take the particular case of the displacement of the Central Asiatic Plateau into the Indian Ocean, and assume the earth to have perfect adaptability, the poles of rotation and inertia to have originally coincided, and the displacement of the plateau to have taken place gradually in the course of time. During the levelling of the plateau the pole describes a great oval, in the same direction as the earth's rotation. From its initial position it wanders southwards through the North Sea and Germany, crosses through Turkey and Persia, passes the Central Plateau, the north of China, goes east from Yokohama through the Pacific Ocean, and *via* East Siberia back to its original position, and begins its wandering again. The rapidity with which it passes the various places changes; it increases with time and reaches its greatest value as soon as the levelling is ended. At the south and north of the oval it reaches at this time 229 km. in the year, in the east and west only 138 km. The duration of a revolution lies in accordance with this, at the time of the completion of the denudation, between one and two hundred years. Schiaparelli remarks that such motion could not fail to be detected by our instruments even if the displaced mass were only $\frac{1}{10,000}$ part of that of the Asiatic Central Plateau.

Earth supposed to have a delayed capacity for adaptation.

Case 3.—The third and most important case considers an earth with delayed capacity of adaptation. If in such a body the pole of rotation is displaced from its position of equilibrium, stresses arise in consequence of the unsatisfied tendency to take a new form dependent on the new motion. These stresses would never be satisfied in the case of a rigid body (Case 1), and immediately satisfied in the case of a fluid body (Case 2). In the present case they are supposed to be satisfied when the stresses reach a certain strength, or, in other words, when the rotation-pole departs a certain distance k from its position of equilibrium. This distance k is called the adaptation-constant. When it is exceeded the stresses deform the body so as to make the pole of equilibrium move after the pole of rotation.

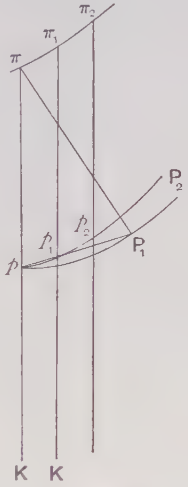

Fig. 105.—Diagram to illustrate Schiaparelli's analysis of the displacement of the pole in an earth with a delayed capacity for adaptation.

In such a body it is clear that, if the pole of rotation never departs farther from the pole of equilibrium, no adaptation will take place and the body will act as if rigid. The results of Case 1 will then apply.

On the other hand, if through some geological cause, for example the addition of a small mass at a point K (see Fig. 105), the pole of inertia is removed from the pole of rotation by more than $\frac{1}{2}k$, then the body acts at first as if rigid, and the pole of rotation P describes a circle of radius Pπ round π until it attains at P_1 a distance from p equal to k. As soon as this point is reached, adaptation occurs and the pole of equilibrium (original position of all the poles) moves to p_1, so that p_1P_1 becomes again equal to k. It is clear that as a result of this the pole of inertia π must take up a new position π_1, the added mass at K still acting and being itself displaced. The earth is now once more in the condition of a rigid body, and P_1 begins to describe a new Eulerian circle round π_1, but the distance k is immediately exceeded, adaptation occurs at once, and p_1 moves after P_1 as before. It is clear, therefore, that the pole of inertia, the pole of rotation, and the pole of equilibrium all describe curves dependent on one another, which curves replace the simple Eulerian circle of the rigid body, and are obviously capable of shifting the pole into temperate latitudes.

Now we do not know the value of the adaptation-constant of the earth. All we can be sure of is that it is not zero, since the earth has clearly a certain amount of rigidity. But even if we knew it we would still be in a difficulty, for we cannot tell if geological changes have ever in the past removed the pole of inertia from the pole of equilibrium, a distance larger than $\frac{1}{2}k$, so that the description of an Eulerian circle must result in the limit being exceeded.

This analysis has the advantage of proving the possibility of motion of the pole, hitherto regarded as inconceivable.

CHAPTER XIV

THE ASTRONOMICAL THEORY

Preliminary statement—Precession of the equinoxes—Its effect on the seasons—Adhémar's theory—Effect of increase in the eccentricity of the earth's orbit—The perturbing influence of the planets—Deduction from Kepler's law—Equality of the total sun-heat received by the earth in summer and winter—Ball's theorem—Equality of the total sun-heat received by the two hemispheres in any year—Increased contrast between summer and winter sun-heat under the supposed glacial conditions—Ball's statement for the whole hemisphere—The relation between sun-heat and temperature—Culverwell's statement of the contrast for special latitudes—Sir George Darwin's presentation of the theory—Culverwell's three comparisons—Importance of transferred heat—Calculation of the dates of the maxima of eccentricity—Summary—Meteorological effects tending to accentuate the effect of increased contrast between the seasons—Effect of the winter snow on the succeeding summer—Importance of the power possessed by water of storing cold and dispersing heat—The reflecting power of snow—Croll's speculation as to the effect of fogs—The Gulf Stream—Atmospheric circulation—Heat-transporting power of water-vapour—Potential energy of expansion—Contrast between the views of Croll and Wallace.

The theory stated.

THE astronomical theory of Croll refers the glaciation of Northern Europe and America to a time or times when, the eccentricity of the earth's orbit being considerably greater than at the present day, the northern summer occurred in perihelion. To make the meaning of this clear to those who have not a previous acquaintance with the subject it will be necessary to recall some elementary astronomy. Every one will have learned at school that the earth, like all the other planets, describes an ellipse round the sun, and that the sun occupies not the centre of the ellipse but one of the foci. The earth is therefore considerably nearer the sun at one end of its elliptic orbit (*i.e.* in perihelion) than at the other (aphelion), and consequently receives more heat per day when at this end. This is not, however, the cause of the seasons, which are due to the fact that the earth's axis is not perpendicular to the plane of its orbit, but is tilted over at a considerable angle, presenting, as it describes its orbit, first one hemisphere and then the other more directly to the sun's rays. At present, when in perihelion it presents the southern hemisphere to the sun, and when in aphelion the northern. The southern summer is therefore, as regards quantity of direct sun-heat, hotter than the northern, but it also follows, of course, that its winter is colder.[1]

Precession of the equinoxes.

This, however, was not always the case, for the earth's axis is slowly changing its position in space, while maintaining approximately the same inclination to the plane of the orbit. It is very slowly swinging round and round in a circle or cone about a line perpendicular to the plane, but it takes the enormous time of 21,000 years to complete the circuit. It follows from this that every year the northern hemisphere is presented directly to the sun at a slightly different point on the earth's orbit, and in the course of time—as a matter of fact in about 10,500 years from now—it will be presented directly to the sun when the earth is in perihelion, and not as now when it is in aphelion. Then the northern summer will be hotter and the northern winter colder than the southern.

This effect is usually referred to as the precession of the equinoxes, the equinoxes, like the solstices, occurring at slightly different parts of the earth's orbit every year. The line of intersection of the plane of the equator and the plane of the earth's orbit, which is known as the line of equinoxes because the latter occur twice a year when it is directed towards the sun, rotates through 360° and returns to its original position in the precessional period of 21,000 years.

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[1] As a matter of fact this effect is entirely counteracted by the greater extent of water, which tends to equalise the seasons. The combination of more abundant precipitation with the greater contrast of sun-heat in summer and winter may be responsible for the more extensive glaciation of the southern hemisphere at the present day.

Effect of precession on the seasons.

It appears, therefore, that as a result of the precession of the equinoxes there may arise two extreme cases which are exhibited diagrammatically in Figs. 106, 107. In Fig. 106 the northern summer occurs in aphelion, and we have the climate of the present day. In Fig. 107 it occurs in perihelion, and we have a climate with more contrasted seasons in the northern hemisphere.

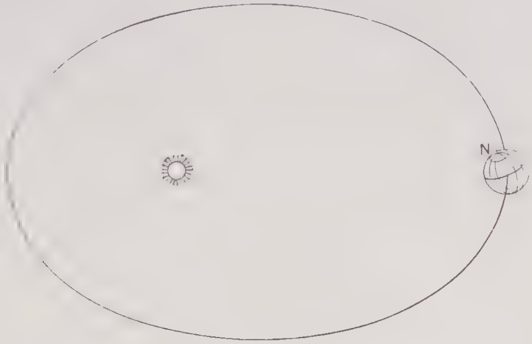

FIG. 106.—Diagram of the earth's orbit showing the relative position of the earth and sun when the northern summer occurs in aphelion, supposed condition for an interglacial period in the northern hemisphere at the maximum of eccentricity. (Case B.)

Consider now the case (Fig. 107) when the northern summer is in perihelion. It is clear that the path of the earth between spring and autumn equinox is decidedly shorter than that between autumn and spring equinox. Moreover, this course is traversed at a faster rate. The summer being thus decidedly shorter than the winter, we have in the northern hemisphere:

(1) In Case A a short hot summer and a long cold winter;

(2) In Case B, similarly, a long mild summer and a short mild winter.

In the southern hemisphere we have likewise:

(1) In Case A a long mild summer and a short mild winter;

(2) In Case B a short hot summer and a long cold winter.

Adhémar's theory.

Adhémar, who was the first to point out this effect of the precession of the equinoxes, held that it was sufficient to cause periodic glaciation. He considered that in the hemisphere with contrasted seasons the short hot summer would be insufficient to melt the snows of the long cold winter and glaciation would ensue, and he pointed to the great ice-sheets of the southern hemisphere as proof of his doctrine. He supposed the glaciation to swing from pole to pole every 10,500 years.

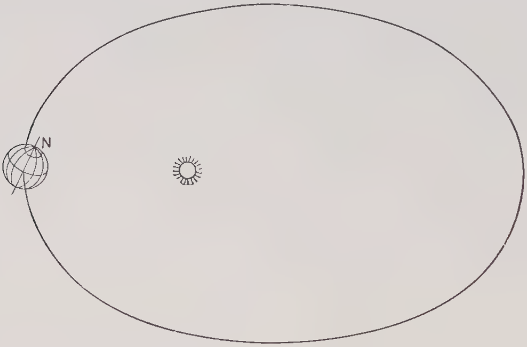

Fig. 107.—Diagram of the earth's orbit showing the relative position of the earth and sun when the northern summer occurs in perihelion—supposed condition for glaciation of the northern hemisphere at the maximum of eccentricity. (Case A.)

Effect of increase of eccentricity.

It is evident at once that an increase in the eccentricity of the earth's orbit must increase the contrast when the seasons are contrasted (Case A in the northern hemisphere), and still further reduce the contrast in the opposite case (Case B in the northern hemisphere). In Case A an increase of eccentricity not only makes the sun nearer in summer and farther in winter, not only shortens the summer course of the sun and lengthens its winter course, but causes the summer course to be traversed more quickly and the winter course more slowly. The greater summer heat is concentrated into a shorter period, and the lesser winter heat spread over a longer period.

Variation in the eccentricity of the orbit.

Now the eccentricity of the earth's orbit is altered at certain intervals by the disturbing effect of the attraction of the other planets, the greater part of the perturbation being, naturally, due to Venus. According to Laplace's theorem of the stability of the planetary system, the effect of these perturbing influences is strictly limited. In no case can the eccentricity of the orbit exceed a certain ascertainable value. It is required to determine what effect, if any, the attaining of this limiting value will have on the climate of the earth. We have first to discuss one or two principles bearing on the distribution of heat.

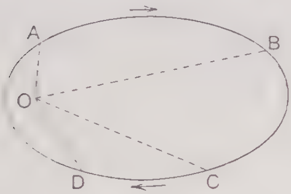

Fig. 108.—Diagram of an elliptic orbit to illustrate the law that the heat received is proportional to the angle swept out by the radius vector.

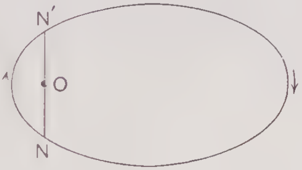

Fig. 109.—Diagram to illustrate special case of the heat law.

Heat received in summer and winter by the whole earth.

In the first place, it will facilitate the understanding of what is to follow if we remember that it can be proved from Kepler's second law that the heat received by the earth in traversing any part of its orbit is proportional to the angle swept out by a radius vector drawn from the sun to the earth. Thus, if the angle AOB (Fig. 108) be twice COD, the heat received from the sun while the earth is passing from A to B is twice that received while it is passing from C to D. As a special case, the heat received in passing from N to N′ (Fig. 109) round one end of the ellipse is equal to that received in passing from N′ to N round the other end. Or, in other words, the heat received by the whole earth in the summer half of the year is equal to that received in the winter half; and this is true no matter what the position of the line of equinoxes or what the eccentricity of the orbit. The precession of the equinoxes and the variation of the eccentricity have absolutely no effect on the equal proportions of heat received by the earth as a whole in summer and winter.

Total yearly sun-heat of hemisphere.

It can also be proved geometrically that the total amount of heat received on the northern hemisphere in the year is equal to that received on the southern hemisphere, no matter what the position of the line of equinoxes. These two problems seem to show that there can be little or no effect of the kind we are looking for. There is, however, another point of view which we have as yet only touched upon.

Seasonal contrast for the whole hemisphere.

We have pointed out above that the effect of an increase in eccentricity is to heighten the contrast between the season in the hemisphere which has its summer in perihelion. We will consider now more exactly what this means. Let us first, following Sir Robert Ball, consider the hemisphere as a whole. It is clear that the quantities of heat received by, say, the northern hemisphere in its summer and winter are very unequal. The proportions are, however, independent of the eccentricity of the earth's orbit and of the position of the line of equinoxes, and depend solely on the obliquity of the ecliptic. With the present obliquity, of the total amount of heat received from the sun on a hemisphere of the earth in the course of a year, 63 per cent is received during the summer and 37 per cent during the winter. Or, if each hemisphere receives in the year a quantity of sun-heat represented by 365 units, then 229 come during summer and 136 during winter.

Now, if the maximum eccentricity of the earth's orbit be taken as ·071, the greatest difference between summer and winter will be about 33 days, giving a summer of 166 days and a winter of 199.

Comparison of glacial, inter-glacial, and present conditions.

Now, combining this with the distribution of heat between the seasons, we get for a maximum of eccentricity and the summer in perihelion, *i.e.* in the supposed glacial climate:

229 heat-units spread over 166 days	Glacial:
136 heat-units spread over 199 days	

while at present

229 heat-units are spread over 186 days	Present.
136 heat-units are spread over 179 days	

Similarly, with the summer in aphelion we get for the supposed interglacial conditions:

229 heat-units spread over 199 days	Interglacial.
136 heat-units spread over 166 days	

Or, if the mean daily heat for the whole year on one hemisphere be represented by unity, we have:

Glacial

Mean daily sun-heat in summer of 166 days . .	1·38
Mean daily sun-heat in winter of 199 days . .	·68

Present

Mean daily sun-heat in summer of 186 days . .	1·24
Mean daily sun-heat in winter of 179 days . .	·75

Interglacial

Mean daily sun-heat in summer of 199 days . .	1·16
Mean daily sun-heat in winter of 166 days . .	·81

Connexion between sun heat and temperature.

These figures, according to Sir Robert Ball, exhibit a thermal force of great intensity. The unit represents the mean daily heat received from the sun by which the hemisphere is warmed up from the "temperature of space." "The heat-unit in fact maintains a temperature of perhaps 300° F., or even more, above what the earth would have without that heat. Each tenth of a unit may thus roughly be said to correspond to a rise or fall of mean temperature of 30° F. or more."

I entreat the reader's particular attention to this latter consideration, upon which both Croll and Ball insist strongly. The temperature of the earth's surface is largely maintained by the sun's radiation. If this were removed it would fall nearly to the temperature of space, which is very little above absolute zero. It would be quite justifiable to say that the temperature of the earth is maintained by the sun 400° F. above what it would have been if the sun were absent, but for safety the figure 300° F. is taken. A relatively small change in the amount of sun-heat received on a hemisphere may therefore make a very large change in its mean temperature, provided, and this is very important, that there is no compensating transfer of heat by oceanic and atmospheric circulation from the hemisphere that is at the same time receiving its more abundant summer sun-heat. Now this is a subject of which we know very little, and we are by no means on safe ground in making such an assumption. It seems probable, however, that there cannot be much transfer of energy by atmospheric currents across the belt of equatorial calms which separates the north and south trades. The centre of this belt, on account of the superior force of the southern trades, lies at present some distance north of the equator. Sir Robert Ball's figures are therefore not strictly applicable even at the present day. To gauge what effect would be produced by having more contrasted seasons in one of the hemispheres and less contrasted in the other would require a knowledge of the connexion between meteorological conditions, sun-heat, and the distribution of land and water which we do not at present possess.

The presentation of the argument in the above form, in terms of the heat-supply of a whole hemisphere, has been taken exception to by Sir George Darwin and Mr. E. P. Culverwell, who consider it more to the point to take account only of the variations of the sun-heat received in the higher latitudes. Thus Mr. Culverwell points out that Sir Robert Ball has only weakened the argument by the introduction of the ratio 63 to 37, which represents the proportion of summer to winter sun-heat over the whole hemisphere. For higher latitudes the ratio is considerably greater. For latitude 50° it is 73 to 27 (nearly 3 to 1); for latitude 60°, 82 to 18 (more than 4 to 1); and for latitude 70°, 91 to 9 (more than 10 to 1). Owing to the efficiency and rapidity of the atmospheric circulation, however, it seems likely that the figures for the whole hemisphere may have considerable significance. In introducing the reader to the more general problem of the seasonal contrast in any latitude, we cannot do better than quote word for word the admirably clear and concise statement given by G. H. Darwin in his review of Sir Robert Ball's book.

Seasonal contrast for particular latitudes.

More general statement of the argument.

> Let the year be divided into only two seasons, viz. the northern summer or southern winter, when the sun is north of the line, and the northern winter or southern summer, when the sun is south of the line. Also let similar days in summer and winter be defined as days on which the sun sets (say at Greenwich) as much after 6 P.M. as before 6 P.M.; similar parts of summer and winter will mean parts limited by similar days.
>
> Now consider the solar heat incident on any specified area of one hemisphere, during any specified portion of the summer, and during the similar portion of the winter. Suppose that the heat incident on the area in the portion of summer, added to that incident on it during the similar portion of winter, be denoted by 2, and suppose that the excess of the heat incident in the portion of summer, above that incident in the similar portion of winter, be denoted by $2a$; then it is clear that $1+a$ is proportional to the amount of heat received by the specified area during the specified portion of its summer, and $1-a$ is proportional to the amount of heat received by the area during the similar portion of winter. Thus, we may say that the contrast between the summer and winter supplies of heat (for given area and given portions of summer and winter) is represented by the fraction $\left(\frac{1+a}{1-a}\right)$.
>
> This is, of course, equally true when the whole hemisphere, and the whole of summer and winter, are considered, and Sir Robert Ball shows that a is then equal to $2 \sin 23° 27'$; $\left(\frac{1+a}{1-a}\right)$ is found to be almost exactly as 5 to 3. Using percentages, he gives the ratio as 63 to 37, but the simple numbers 5 to 3 afford a closer approximation to accuracy.

It is clear that if the specified portions of summer and winter embrace the solstices, and if the specified area is tropical, a will be small, and if it is polar, it will be large. The fraction $\left(\frac{1+a}{1-a}\right)$ continually increases as we go northward, and it may be taken as a measure of the severity of a climate. It is quite uncertain how far the climate of any one place depends on the heat supplies of the whole hemisphere on which it lies, and therefore it is uncertain how large an area and how long a season we ought to take into consideration in the present investigation. But I should have thought it legitimate, in treating of the causes of glaciation, only to consider the semi-annual heat-supply of a polar cap, comprising, say, all the area north of latitude 30°; this would have made $\frac{(1+a)}{(1-a)}$ much greater than 5 to 3. It does not seem to me, however, that we are bound to find an answer to this almost insoluble problem.

So far we have considered the supply of heat whilst the earth describes so many degrees of longitude round the sun, but climate depends on the supply of heat during a given time.

When the earth's orbit is circular, summer and winter are of equal length, and so also are similar portions of summer and winter; thus the two ways of estimating the heat-supply coalesce, and the contrast between the summer and winter daily supplies of heat is also represented by the fraction $\frac{(1+a)}{(1-a)}$. The present condition of affairs differs but little from this standard case, and we know that the contrast between the summer and winter daily supplies of heat is such as to produce certain known climates, differing according to latitude. The question we have to ask is, if the orbit becomes eccentric how will the contrast of daily supplies be affected?

In order to answer this, let us go at once to the extreme, when the eccentricity of the orbit is a maximum. We learn that if aphelion is at midsummer, summer will be 199 days, and winter 166 days; and the converse is true when the perihelion is at midsummer.

Since 199 is to 166 nearly as 6 to 5, we see that with midsummer perihelion there are 5 days of summer to 6 of winter, and with midsummer aphelion there are 6 of summer to 5 of winter.

Hence, with midsummer perihelion, the short summer daily supply of heat may be taken as proportional to $\frac{1}{5}(1+a)$, and the long winter daily supply as proportional to $\frac{1}{6}(1-a)$. Hence the contrast between the short summer and long winter daily supplies is represented by $\frac{6\,(1+a)}{5\,(1-a)}$: that is to say, the standard contrast is augmented in the ratio of 6 to 5. Next, with mid-summer aphelion, the long summer daily supply of heat may be taken as proportional to $\frac{1}{6}\,(1+a)$, and the short winter daily supply as proportional to $\frac{1}{5}\,(1-a)$. Hence the contrast between the long summer and short winter daily supplies is represented by $\frac{5\,(1-a)}{6\,(1-a)}$: that is to say, the standard contrast is diminished in the ratio of 5 to 6.

In the first case, the heat-supply is less evenly distributed through the year than at present, and we have a much more severe climate: in the second, it is more evenly distributed, and we have a much milder one. It follows also that, if we compare the two extreme cases together, instead of both with the mean case, the change of contrast is represented by the ratio of 6^2 to 5^2, or of 36 to 25.[1]

Culverwell's estimate of the increased contrast for the higher latitudes.

Mr. E. P. Culverwell[2] has made a substantial contribution to our knowledge of the subject by following out to its logical conclusion the theorem just outlined. His method is to ascertain what parallel of latitude now receives the same winter sun-heat as, say, parallel 50° received in the period of great eccentricity when the winter was in aphelion. (1) Following Croll's idea, he finds what parallel now receives the same mid-winter sun-heat; (2) following Ball's method, he finds what latitude now receives the same daily average of sun-heat in winter, *i.e.* from equinox to equinox; and (3) he finds what latitude now receives the same total amount of sun-heat in its coldest 199 days as latitude 50° did in the 199 days of the supposed glacial winter. He makes similar calculations for all latitudes from 40° north with the following results:

FIRST COMPARISON

As regards the amount of sun-heat received on mid-winter day,

latitudes	43°	52°	61°	70°	80°	90°	at present
are comparable with	40°	50°	60°	70°	80°	90°	in the period of great eccentricity.

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[1] G. H. Darwin, "The Astronomical Theory of the Glacial Period," *Nature*, vol. xlv. p. 289 (1892).

[2] E. P. Culverwell, "A Criticism of the Astronomical Theory of the Ice Age and of Lord Kelvin's Suggestion in connection with a Genial Age at the Pole," *Geol. Mag.* Dec. iv. vol. ii. pp. 3 and 55 (1895).

SECOND COMPARISON

As regards the daily average of sun-heat in winter,

latitudes	43·3°	52·4°	61·7°	71·3°	81°	90°	at present,
are comparable with	40°	50°	60°	70°	80°	90°	in the period

of great eccentricity.

THIRD COMPARISON

As regards the total amount of sun-heat in their coldest 199 days,

latitudes	42·2°	54°	63·5°	74°	84·5°	..	at present
are comparable with	40°	50°	60°	70°	80°	90°	in the period

of great eccentricity.

Importance of atmospheric and oceanic circulation.

Mr. Culverwell points out with great justice that a change in sun-heat such as is here indicated could not possibly have the effect of producing a glacial period. These figures, however, only take count of the sun-heat received directly, and this, as he is very careful to state himself, only forms a certain proportion of the total heat received by any latitude. A large amount of heat is transferred from lower latitudes by atmospheric and oceanic circulation, and there is a diminution in the amount of this heat during the severer winter of the period of high eccentricity as well as in the direct sun-heat. I am inclined to think that it is in considering the change in the heat-supply from this source that the figures of Sir Robert Ball have their value. For these figures to be in any way accurate, it would be necessary that there should be no transfer of heat across the equator by circulation, and this we have seen is certainly not the case at the present day. We can hardly assume that it was any more the case during the period of great eccentricity. The figures, therefore, only give a rough indication of the change in the transferred heat received by any northerly latitude. It is clear from them, however, that this change might be very considerable, and might possibly supplement the decrease in direct winter sun-heat sufficiently to bring about glacial conditions.

Dates of the maxima of eccentricity.

Croll, using Laplace's formula, made calculations for the purpose of fixing approximately the dates of the maxima of eccentricity for the last three million years.

According to Sir Robert Ball, this formula is hardly of sufficient accuracy to justify its use over such immense periods of time. It is not unlikely, however, that it gives an approximate result for the more recent maxima. In the accompanying figure the results are shown for the last 300,000 years, the precessional periods of 10,500 years being shown by black and white bands.

Summary of conclusions.

We have now considered the leading astronomical factors on which Croll's theory depends, and we have seen that there is neither any change in the amount of sun-heat falling on the whole earth during summer or winter, nor any change in the total yearly sun-heat received by a hemisphere. The effect is totally one of increased contrast of seasons in the one hemisphere and reduced contrast in the other. Whether the increased contrast would indeed lead to glaciation can hardly be determined at present. Croll thought that it certainly would, for he considered that the greater heat of the short summer would be entirely inadequate to melt the accumulated snows of the protracted and cold winter. His figures and those of Sir Robert Ball are rather impressive in their presentation of the increase in contrast brought about by the astronomical conditions, and the theorem as stated by G. H. Darwin seems no

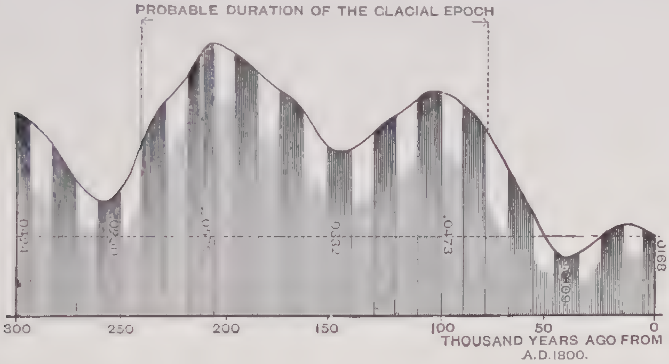

FIG. 110.—Diagram showing the more recent changes of eccentricity of the earth's orbit. (After Wallace.)

less effective. Mr. Culverwell's estimate, however, in terms of latitudes of equivalent sun-heat, is certainly of a nature to give one pause in jumping at conclusions as to the effectiveness of the change. It must be remembered, however, that the figures quoted only represent the results of the decrease of direct sun-heat, and take no account of the decrease in the amount of heat transferred from lower latitudes.

Having thus presented the astronomical elements of the theory in their strength and in their weakness, we must leave the reader to form his own opinion as to their efficiency. He will, I venture to think, conclude that there is here at least a tendency in a direction favouring greater precipitation in the form of snow, that is to say, in the direction of glaciation.

Meteorological effects of increased contrast.

Croll, seeing clearly that there could be no decrease in the total sun-heat received during the year, realised that the theory could not rest directly on the astronomical data, but that the cooling effect must be in some way the result of the increased contrast of summer and winter. Among the meteorological effects invoked by him to eke out the astronomical data, the most powerful is undoubtedly the influence of the snow accumulated during winter on the conditions of the succeeding summer. He held that the snow-fields would have such a chilling influence on the warm, moisture-laden winds of spring and summer, that still further snowfall would result. No doubt there is such an effect, but it is more difficult to see where the gain in the direction of glaciation comes in. If heat is abstracted from the wind, it goes towards raising the temperature of the snow, which is therefore more easily melted by subsequent warm winds. Mr. A. R. Wallace has, however, put the argument in a more effective form by pointing out that the struggle between the winter cold and the summer heat as regards the accumulation of snow is an unequal one. On account of the freezing-point of water being such as it

Struggle between winter accumulation and summer melting.

is, cold can, so to speak, be stored indefinitely whereas heat cannot. Precipitation reaching the ground in the form of snow stays where it is, and must have imparted to it either by sun or wind not only sufficient heat to raise it to freezing-point, but all its enormous latent heat of melting, before it becomes water again and is capable of motion. Rain, on the contrary, flows off along the drainage channels at once, and any heat over and above what is sufficient to keep it liquid is carried away into the sea. To use a metaphor, winter is continually piling up in the snow-fields its savings of cold, and there is no cold so great that it cannot hoard every bit of it, while summer can but pay its debts to winter by raising the temperature of the snow to zero; and if it ever effects more than this and produces water with a reserve of heat, that reserve, together with all the latent heat of melting, is at once removed from the land into the ocean, where it becomes infinitely less effective in preventing glaciation. The advantage on the side of winter is obvious.

It is, of course, a truism to say that glaciation depends largely on the amount of precipitation, but how much more meaning the statement assumes when we realise this power that water possesses of storing cold and dispersing heat. In areas of abundant precipitation a very slight increase in the contrast between the seasons might, therefore, lead to an immense growth in the existing snow-fields, and might bring about the formation of permanent snows in mountain regions, such as Scotland, which lie just beneath the snow-line.

Reflecting power of snow.

Great importance is also attached by Croll to the reflecting power of snow. The sun's rays in passing through the atmosphere undergo selective absorption, only those rays to which the atmosphere is relatively transparent reaching the earth's surface. If they are here absorbed and only given out again by radiation, their wave length is changed, and they undergo still more powerful absorption on their outward course. When reflected, however, they remain unaltered in character, and there is little or no further absorption, nearly all the rays which are capable of being abstracted by the atmosphere having already been removed.

Blanketing effect of fogs.

Croll is on more doubtful ground when he discusses the effect of fogs in lowering the temperature of glaciated regions. There is no doubt that the presence of fog over a snow-field would exercise a blanketing effect and protect the snow from the direct radiation of the sun. The experience of modern explorers, however, tends to show that the air over the great ice-sheets is in general of remarkable clearness, so that in the light of modern knowledge we must regard any effect of this kind as confined to the smaller ice-caps and glaciers.

The Gulf Stream.

An account of Croll's views would be incomplete without some mention of his famous discussion of ocean currents, and of the Gulf Stream in particular. He considered that the steeper temperature gradient from the equator to the pole in the glaciated hemisphere would increase the strength of the trade-winds, and that the warm water of the tropical oceans would then be driven over in considerable quantities into the warm hemisphere. During the glaciation of the northern hemisphere, for example, owing to the supposed augmented strength of the northern trade-winds, the east and west equatorial current, which feeds the Gulf Stream, would be displaced farther to the south, and a far larger proportion of it than at present would impinge on the coast to the south of Cape St. Roque and so be deflected south along the shores of Brazil into the southern ocean. A diminution in the volume and power of the Gulf Stream would result, and the temperature of the North Atlantic and of North-western Europe would be considerably lowered. It is to be noted at the outset that this partial depletion of the Gulf Stream is supposed to result from the presence of already accumulated snow and ice, and not directly from the astronomical causes. It is one of Croll's cumulative effects whereby the glaciation once started is supposed to have augmented itself. It can in no way increase the contrast between the seasons, for, as Mr. Culverwell points out, the Gulf Stream between the Azores and Ireland only travels 3·9 miles per day, or 10 degrees in six months. The sun-heat received by it in summer is only carried 10 degrees north before the succeeding winter, so that it is inevitable that the tendency is, if anything, to diminish the contrast of seasons in the region towards which it flows. It cannot be denied, on the other hand, that a decrease in the volume or velocity of the Gulf Stream would lead to a considerable general lowering of temperature. The connexion between the glaciation and the trade-winds cannot, however, be regarded as established.

Slowness of the Gulf Stream.

I venture to think that Croll considerably exaggerates the relative importance of ocean currents as transporters of energy. It would be foolish to deny that their effect is immense, but, on the other hand, it is going too far to hold, as Croll did, that it is out of all proportion greater than that of the atmospheric circulation. In making the comparison Croll compares the specific heat of water with that of air, and concludes that an air current to carry the same amount of heat as an ocean current of the same velocity would need to be 3234 times its volume; or if we assume the air current to have ten times the velocity of the ocean current, it will need to be 323 times the volume of the latter. In this estimate, however, as he later points out, he has not included the enormous heat-bearing power of water-vapour, which is so great that, in the condensation of one pound of water from a state of vapour at low temperatures, sufficient heat is given out to raise 600 pounds of water one degree. As Croll, however, considers that the greater part of the evaporation of the tropics falls as rain within the tropics, and that the upper or anti-trade air currents must lose practically all their moisture before descending again north of the trade-wind belt, he does not think that much of the equatorial heat is carried northwards in this way. He considers that the descending air brought

Importance of atmospheric circulation.

north by the anti-trades must have lost both its heat and moisture, the former by radiation and the latter by precipitation, and must be cold and dry when it descends. This is no doubt to a great extent true, but it can hardly be that all the energy is lost in this way, and we have at present no knowledge of what proportion is lost and what retained.

Energy of expansion.

There is, moreover, an aspect of this question which Croll does not appear to have considered. The air of these upper currents, in virtue of its expanded state, contains an amount of potential energy which becomes available as heat on its descent to the surface of the earth in the temperate regions. It acquires this energy by precipitating its contained water-vapour as it rises in the equatorial regions, and maintains its temperature in spite of radiation as it travels north by precipitating more moisture. When, therefore, it commences to descend its temperature need not necessarily be very low, and when it has come down into regions of greater pressure and set free its potential energy in the form of heat, it may, like the foehn winds of the Alps, be quite warm instead of, as Croll assumes, necessarily below freezing-point.

The actions of the various phenomena we have just discussed are so complex, and their laws so little understood, that anything in the nature of a reliable estimate of their efficiency is at present quite impossible. I think, however, it is clear from some of the above considerations that there may well be, as Croll held, a cumulative effect in the growth of glaciers and ice-sheets, that in fact the climate is in this direction somewhat unstable, and any cause tending directly to produce slight glaciation might ultimately, by indirect means, lead to the formation of immense ice-sheets.

Wallace's views on the inter-glacial question.

We now come to a point of great importance on which Mr. A. R. Wallace parts company with Croll. Croll believed that the ice-sheets only persisted throughout that portion of the precessional period during which the winter occurred in aphelion, that is to say, throughout the period of contrasted seasons, and that they died away almost completely in the period of cool summers and mild winters when the summer occurred in aphelion. He thus imagined the glaciation to swing from pole to pole every precessional period, and the glacial periods to alternate in each hemisphere with mild interglacial periods. Wallace thought that once the ice-sheets had established themselves they persisted throughout the whole period of high eccentricity, and that the precessional changes only caused oscillations of the ice margin. and possibly the almost complete temporary disappearance of smaller glaciers farther south. As geological evidence in support of Croll's idea of complete interglacial disappearance of the ice-sheets is almost entirely wanting, and as much doubt has been thrown on the few isolated cases which seem of importance in this respect, it seems preferable to accept Wallace's form of the theory. if any. This has the advantage of not being inconsistent with the trend of modern glacial investigation, which seems, in the case of the ice-sheet of Northern Europe at least, to point to the singleness or perhaps simple bipartition of the glaciation. Moreover, it does not exclude the possibility of a certain amount of marginal oscillation, and of this we undoubtedly have evidence, and it explains the almost complete interglacial disappearance of the glaciers of the Alps, which we may regard as clearly established by the work of Penck and Brückner.

CHAPTER XV

THE LATE QUATERNARY OSCILLATIONS OF LEVEL IN FENNOSCANDIA

The Yoldia Sea—Rise of the sea in the wake of the retreating glaciers—The deposits of the Christiania Valley—The Yoldia maximum of submergence –The isobases of the late-glacial depression—The late-glacial recovery—Wave-like progress of the uplift—The post-glacial shell-banks of the Christiania region—The Tapes submergence—Its northern limit in the Christiania region—De Geer's estimate of late-glacial and post-glacial time—History of the Baltic—The Baltic Ice Lakes and the Zanichellia Sea—The distribution of Yoldia in the Yoldia Sea—*Idothea entomon*—The marginal terraces of Vaberg—The Ancylus Lake—The Ancylus transgression in Gotland—The climate of Ancylus time—The late Ancylus emergence—The Littorina submergence—Significance of the submergence of the late Ancylus outlet—Munthe's researches on the salinity of the Littorina Sea—Isobases of the Littorina Sea—Identity of the Littorina and Tapes stages—The kitchen-middens and the Campignien immigration—Identity of Campignien time with the Littorina-Tapes maximum—Brögger's correlation of the stages of retreat with the sub-stages of the Neolithic Period.

THE honours of post-glacial geology rest undoubtedly with the Scandinavians. Their elaborate and careful investigations into the recent geographical developments of their country have made them justly famous. Living in the midst of problems of an interest perhaps unequalled in any other region, they have attacked them with a scientific spirit worthy of the highest admiration, and evolved from them a story which is one of the romances of modern geology. The researches of Munthe, De Geer, and Holst into the history of the Baltic, and Brögger's investigations in the Christiania region have a world-wide fame, and no less widely known is the work of

Nathorst and Gunnar Andersson on the succession of floras in the post-glacial beds of Sweden.

Late glacial submergence of N.W. Europe.

When the great European Ice-sheet withdrew finally towards its centre of distribution east of the Scandinavian mountains, it left the north-west of Europe under very different conditions from those which prevail at present. Denmark, the southern low-lying parts of Sweden and Norway, and most of the coastal lands of the Baltic, were submerged beneath the sea. A great open arm of the Atlantic stretched at that time into the basin of the Baltic, and extended over the Russian plain, joining in all probability with the Arctic Ocean by way of the White Sea. Raised beaches and stratified clays with marine shells are found up to considerable heights in many parts of the area. The shells are those of molluscs quite different from such as are now found living round the coasts of Sweden and Norway, and more closely allied to forms at present confined to the colder parts of the Arctic Ocean. One of them, *Yoldia arctica*, Gray, now only lives in sea-water at a temperature below 0° centigrade, and thrives in the muddy waters discharged at the mouths of glacier streams. Its remains are abundant in the deposits of the sea which occupied the basin of the Baltic in late-glacial times.

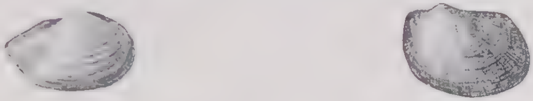

FIG. 111.—*Portlandia* (*Yoldia*) *arctica* and *Arca glacialis* from the Late Glacial Marine Clays of Norway. (After Brögger.)

The Yoldia Sea.

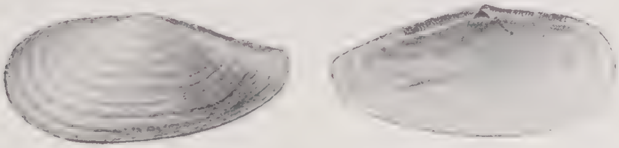

FIG. 112.—*Yoldia hyperborea* from the Late Glacial Marine Clays of Norway. (After Brögger.)

This has in consequence come to be known as the Yoldia Sea. A little crustacean, *Idothea entomon*, L., found along with Yoldia in these deposits, is also a characteristic form of the Arctic Seas. Unlike the molluscs which accompanied it, it has not become extinct in the Baltic basin, but persists in a stunted form in that sea itself and in some inland lakes formerly connected with it.

Glacial character of the Yoldia Sea.

The deposits of the Yoldia Sea show every trace of the presence of floating ice. The beds are often contorted and disturbed as if by its grounding. That the disturbances were contemporaneously produced is proved by the fact that the disturbed beds are often overlain by others absolutely undisturbed. Boulders are often found embedded in the sediments as if dropped in from icebergs or floe-ice.[1]

Relation of the sea to the retreating glaciers.

The exact relations of the sea-level to the retreating glaciers have been worked out in detail by Professor Brögger [2] in the Christiania region. He has shown that during the first stages of the retreat, when the outer moraines were deposited, the land became submerged beneath the sea as the glaciers retired. This submergence continued for some time, and then a reverse movement set in, and from that on the land emerged continually. We will best exhibit the relations by tracing in succession the stages of retreat of the ice-margin, and the position of the sea-level in regard to them.

The moraines of the Christiania Valley, taken in order from without inwards, are :

The outer ra-moraine.
The inner ra-moraine.
The moraine between the inner ra and the epiglacial moraine.
The epiglacial moraine.
The moraines between the epiglacial moraine and the uppermost moraine.
The uppermost moraine.

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[1] See Gerard de Geer, "Om Skandinaviens Geografiska Utveckling efter Istiden," *Sveriges Geologiska Undersökning*, Ser. C. No. 161a.

[2] W. C. Brögger, "Om de Senglaciale og Post-glaciale Nivåforandringar i Kristianiafeltet," *Norges Geologiska Undersgelse*, No. 31 (1901).

The retreat of the ice from the epiglacial moraine signalised the commencement of the emergence of the land which continued into post-glacial times, and brought to an end the so-called Christiania Period which was characterised throughout by progressive submergence.

The initial period of progressive submergence.

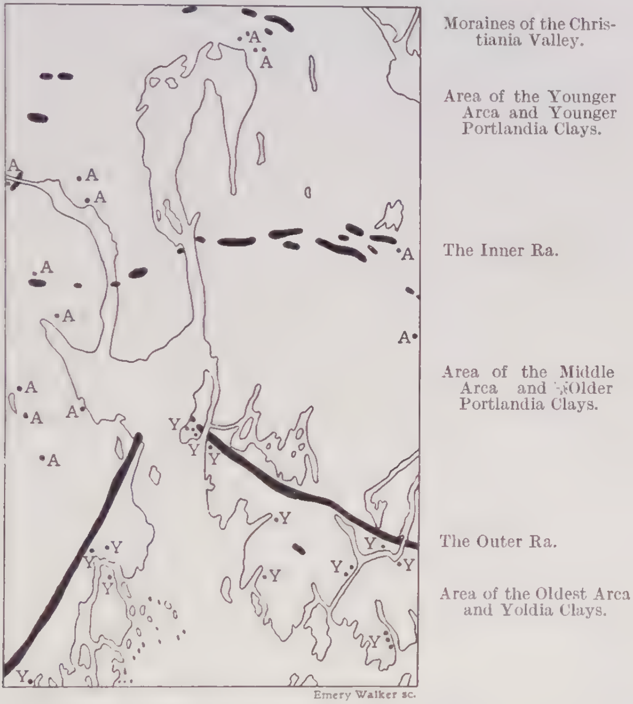
Moraines of the Christiania Valley.
Area of the Younger Arca and Younger Portlandia Clays.
The Inner Ra.
Area of the Middle Arca and Older Portlandia Clays.
The Outer Ra.
Area of the Oldest Arca and Yoldia Clays.
A
Y
Emery Walker sc.

Fig. 113.—Map of the Christiania Fjord, showing the successive moraines and the intervals on which were deposited the various marine clays. Localities of the Yoldia Clay are marked Y, and of the Arca or Portlandia Clays, A. (After Brögger.)

That the ras of Christiania are not terminal moraines in the sense of marking the extreme limit of advance in a glacial period, is considered by Brögger to be proved by the fact that the country outside and inside them does not differ, the striae on both sides being equally fresh and in the same direction. They merely mark a halt in the retreat of the glaciers of the great Ice Age.

The Older Yoldia Clay.

Resting on the till and glaciated surfaces outside the outer ra-moraine are stratified marine clays, from which have been obtained twenty-six species of mollusca, all high arctic and nearly all living in the Kara Sea. This is the Older Yoldia Clay. It is deposited against the outer slope of the ra-moraine, and is never found inside it. Its altitude in the neighbourhood of the ra is 40 to 50 metres, but it also occurs right down to sea-level. Now the typical and common species obtained from it live in abundance in the Arctic Seas only at depths of from 10 to 30 metres. Deeper water species have never been found in it. It is clear, therefore, that the vertical range of the fossil shells in the Christiania region is greater than their possible vertical range on the assumption of a constant sea-level. From the occurrence of the clay at an altitude of 40 to 50 metres, it may be concluded that the sea stood at 50 to 80 metres above its present level, whereas from its occurrence at sea-level the figures 10 to 30 metres are arrived at. The only way of explaining these apparently contradictory results is to assume that at the beginning of Older Yoldia times the sea stood at the lower level (say 20 metres), and that it gradually rose until it attained the higher level (say 65 metres).

Change of sea-level during (1) the Older Yoldia Clay;

But we have evidence of still further submergence before the glaciers abandoned the outer ra, for resting upon the Older Yoldia Clay outside the moraine, but never inside, are found two other clay deposits, the Younger Yoldia Clay and the Oldest Arca Clay. These occur in direct superposition thus:

Oldest Arca Clay,
Younger Yoldia Clay,
Older Yoldia Clay,

and they pass imperceptibly one into the other.

(2) the Younger Yoldia Clay;

In the Younger Yoldia Clay, which is only 1 to 2 metres thick, many of the arctic species are of reduced size, indicating an amelioration of climate. They also indicate a greater depth of water, namely, 40 to 60 metres.

The sea was therefore still rising, but the characteristic deep-water forms of the succeeding Arca Clay were not yet able to exist in it.

(3) the Oldest Arca Clay ;

The Oldest Arca Clay contains a fauna which is almost quite distinct from that of the Yoldia Clay, only a few forms being common to the two. It is essentially a deep-water fauna, indicating some 80 to 100 metres of water just outside the moraine. It shows that the sea-level must at this time have attained an altitude of about 135 metres above its present level.

The glaciers now abandoned the outer ra and receded some 25 kilometres to the inner ra, leaving a clean space between for the reception of subsequent marine deposits.

(4) the Middle Arca and Older Portlandia Clays ;

On the fresh striated surfaces of this space were deposited the Middle Arca and Older Portlandia Clays. Their fauna indicates an amelioration of climate. *Arca glacialis*, for example, is of smaller size than in the Lower Arca Clay. The Middle Arca Clay is never found inside the inner ra.

A further recession of the glaciers now took place. They abandoned the inner ra and retreated to the moraines of the Christiania Valley, leaving a stretch of country as before for the reception of marine sediments.

(5) the Younger Arca and Younger Portlandia Clays.

On this were deposited the Younger Arca and the Younger Portlandia Clays. The former is a deep-sea clay occupying the lower parts of the valley up to about 100 to 130 metres above the sea, and the latter a shallow-water clay in the higher parts at some 100 to 175 metres above sea-level. The fauna of the Younger Arca Clay is considerably less arctic than those of the preceding clays.

The epiglacial moraines the limit of marine deposits.

On the area left bare by the further recession of the glaciers to the epiglacial moraines south of the large lakes of Central Norway masses of clay and sand were deposited, but only in rare instances do they contain marine mollusca. Inside the epiglacial moraines no marine strata occur. The sea, in fact, at this stage ceased to rise in the wake of the retreating glaciers, and there set in, in the Christiania region, an almost continuous emergence of the land, which has gone on up to the present day.

Let us consider now what general ideas we have arrived at. We have seen that throughout a great part of Scandinavia and Russia in late-glacial times the sea stood at a considerably higher level relatively to the land than at present, and Brögger has established in the Christiania region the all-important fact that it rose as the glaciers retreated. That is to say, that the land, on the departure of the ice, did not find itself in the maximum state of submergence and rise therefrom in consequence of the removal of the weight of the glaciers. The relation is by no means so simple as this. On the contrary, the submergence increased at first as the glaciers diminished, and it was not until a fairly advanced stage of the retreat that the elevation, which appears to have followed upon the disappearance of the ice, first made itself felt. We shall return to this point when discussing the more theoretical aspects of the question of oscillations of sea-level during Quaternary times.

Extent of the submergence.

Throughout the whole of Scandinavia and the basin of the Baltic this late-glacial submergence has left its marks. All along the north-west coast of Norway are found terraces and strand-lines up to considerable heights on the land.[1] In some places several terraces can be seen one above the other, marking different levels of the sea, and it is a matter of some difficulty to correlate these from place to place. It is not even safe to conclude that the highest terraces in different districts are quite contemporaneous. Nevertheless, by drawing a series of isobases for the highest terraces a fairly accurate idea of the nature of the late-glacial and post-glacial warping is obtained. These isobases are lines of equal depression of the land, with regard to the present sea-level, in the

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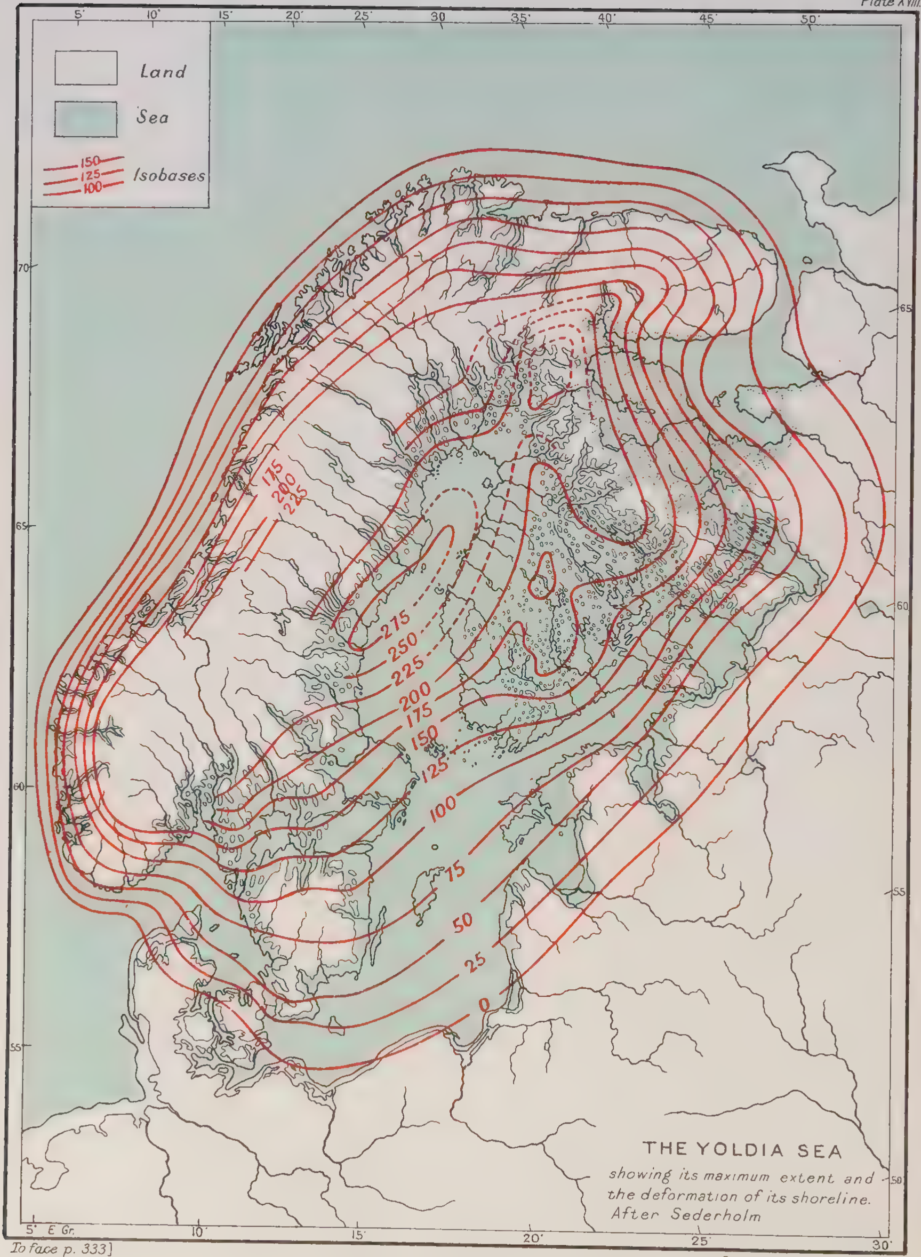
[1] See Gerard de Geer, "Om Skandinaviens Geografiska Utveckling efter Istiden," *Sveriges Geol. Unders.*, Ser. C. No. 161a (1896). Rekstad and Vogt, "Sondre Helgelands Kvartär Geologi," *Norges Geol. Unders.*, No. 29, p. 62 (1900). Helland, "Strandliniernas Fald," *ibid.* No. 28, part 2 (1900). V. Tanner, "Studier öfver kvartärsystemet i Fennoskandias nordliga delar," *Fennia*, vol. xxiii. No. 3 (1906), and vol. xxvi. No. 1 (1907).

Plate XVIII.



THE YOLDIA SEA

showing its maximum extent and the deformation of its shoreline. After Sederholm

To face p. 333]

Stanford's Geog! Estabt, London.

London : Macmillan & Co., Ltd.

late-glacial period of submergence. They are constructed by measuring the altitudes above sea-level of the highest terraces in various places and joining up the localities where the altitude is the same. When drawn they are found to form sweeping curves round about the central portion of Scandinavia, as shown in Plate XVIII. It is at once apparent from the figure that the depression was least in the outlying districts and increased towards the centre of the affected area. That is to say, for example, that if we were to visit some of the outlying islands off the Norwegian coast we would find the highest terraces on them no very great height above present sea-level, but if we then proceeded to the coast of the mainland they would there lie at a somewhat greater height, and this height would increase as we passed up the fjords into the interior of the country. The general result may be stated thus. In late-glacial times an immense oval area with its centre in the Baltic basin, east of the Scandinavian mountains, was depressed to a considerably lower level than that at which it lies at the present day. It can hardly be a mere coincidence that the central area of this depression was the great centre of dispersion of the European Ice-sheet. This has given rise to the idea that the depression was caused by the weight of the ice, and that on the removal of the latter the land has tended to rise once more to its former level. This theory does not, however, explain the period of progressive submergence which has been proved by Brögger in the Christiania region to have preceded the elevation. We must ask the reader to assume for the present that this was due to a general rise of the sea-level, the absolute necessity of which, as a result of the returning to the ocean of the immense quantities of water bound up in the ice-sheets, we shall demonstrate later.

Greater depression of central areas.

Coincidence of depression with centre of dispersal.

Let us return now to the Christiania region, the post-glacial history of which we have traced up to the point when the sea ceased to rise in the wake of the retreating glaciers, and the elevation which set in after the melting

Further history of the Christiania region.

of the ice-sheet first became sufficiently powerful to make itself felt.

Wave-like progress of the uplift.

As the peripheral part of Scandinavia was relieved of its ice-load first, its elevation started at a slightly earlier period than that of the interior of the country. Thus in the south of the Christiania region the elevatory movement gathered force at an earlier date than in the north, and was sooner able to compete with the general rise of the sea. The maximum of submergence in the southern district occurred thus somewhat sooner than in the northern part of the Christiania Valley. The evidence of this remarkable fact lies in the shell-banks laid down during the period of emergence, and these we shall now briefly consider.

These shell-banks occur in the Christiania region at intervals from an altitude of 208 metres down to present sea-level. Brögger classifies them as follows :

(1) The Upper Mya-banks	corresponding to	0-25 %	of the total uplift.
(2) The Lower Mya-banks	,, ,,	25-40 %	,, ,, ,,
(3) The Lowest Mya-banks	,, ,,	40-50 %	,, ,, ,,
(4) The Upper Tapes-banks	,, ,,	60-85 %	,, ,, ,,
(5) The Lower Tapes-banks	,, ,,	85-100 %	,, ,, ,,

Fossiliferous clays are also met with corresponding to these shell-banks, and an exhaustive study has been made of the fauna in several localities, especially in Christiania and Smålenene. This investigation has shown that these series are not strictly parallel in the different places ; that is to say, a bank which corresponds to a definite proportion of the uplift at Smålenene was not formed contemporaneously with one corresponding to the same proportion of uplift at Christiania.

Now the climate at any period must have been much the same at Christiania and Smålenene, and hence the proportion of arctic, boreal, and Lusitanian forms in the fauna may be taken as a criterion for correlating the banks in the two places. In other words, it is simply assumed that the extinction of northern and the immigration of southern forms went on *pari passu* in the two localities, so that the proportions of the various forms gives the relative age of the beds, whether they are in one locality or the other. In this manner the following conclusions are arrived at:

(1) The Upper Mya-banks of Smålenene, which indicate the beginning of the emergence at that place, were deposited at a time when the land at Christiania was still undergoing submergence, and the Youngest Arca Clay was being deposited there.

(2) The Lower Mya-banks of Smålenene, which correspond to a more advanced stage of the uplift (25 to 40 per cent), must have been deposited contemporaneously with the Uppermost Mya-banks at Christiania (0 to 15 per cent of the uplift); while the Mya-banks and Cardium-clay at Christiania, corresponding to 15 to 40 per cent of uplift, were formed at the same time as shell-banks at Smålenene, representing 40 to 50 or 60 per cent of the uplift at that place.

Shell-banks at levels corresponding to the same percentage of total uplift are thus not contemporaneous in the southern and northern parts of the Christiania region, and the uppermost shore-lines in different places are not synchronous. The rise began earlier in the southern peripheral parts of the region, and was, at least during the first half of the uplift, at all times more advanced in these peripheral parts than in the central parts.

The Zirphaea strata of Vendsyssel (the northernmost part of Jutland), although corresponding to about 50 to 80 per cent of the uplift, are in the same way contemporaneous not with the Lower but with the Upper Mya-banks of Smålenene. The maximum of subsidence at Vendsyssel occurred as early as the Older Yoldia Clay, and the land had recovered almost its present level at a time when in the southern part of the Christiania region only one-quarter to one-third of the total uplift was completed.

Similar conclusions have been drawn from the study of the well-known Saxicava-banks in the neighbourhood of Uddevalla (Scania). The general results are shown in Fig. 114, in which the motions of the land with respect to the sea in the various places during the later stages of the glacial period are represented by arrows.

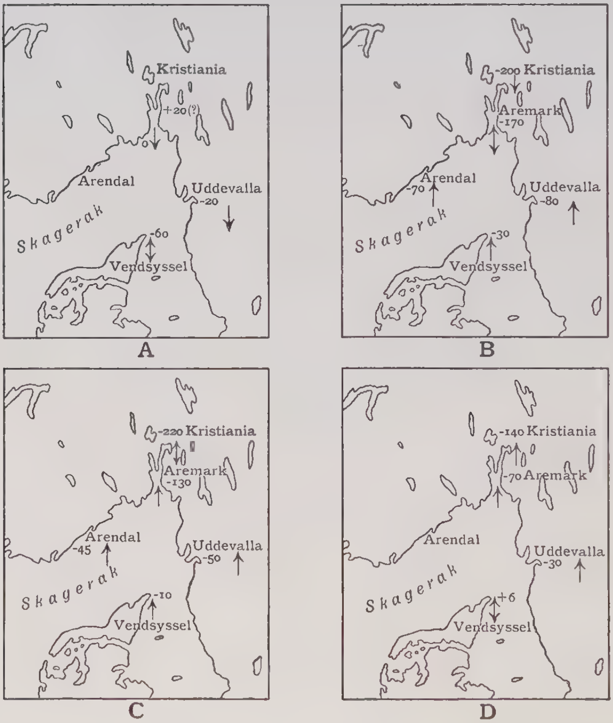


Fig. 114.—Showing the motion of the land relatively to sea-level on the shores of the Skager Rack and Cattegat at successive stages of the late-glacial submergence. The figures indicate in metres the amount of emergence (+) or submergence (−) relatively to the present level. A northward pointing arrow indicates that the land was emerging at any stage, a southward pointing arrow that it was undergoing submergence. A double-headed arrow indicates a maximum of either emergence or submergence, the relative level of land and sea being for a time constant. A comparison of the four diagrams will show the wave-like progress of the uplift from south to north. (After Brögger.)

Period of rapid rise.

Comparatively few shell-banks are known in the Christiania region corresponding to the middle period of the rise (40 to 66 per cent of the total uplift). At levels corresponding to about 66 per cent of uplift the difference in the fauna known from the Mya time in the central and peripheral parts of the country is almost infinitesimal. These facts point to the conclusion that during this period of the uplift the rise must have been more rapid in the neighbourhood of Christiania than farther south. In this period of rapid rise Brögger places the boundary between late-glacial and post-glacial time, considering the latter to correspond to 50 or 60 per cent of the total uplift at Christiania.

In the oldest beds of the post-glacial period, the Upper Tapes and Ostrea-banks, the fauna shows a great difference from that of the Mya-banks. There are but few arctic species, and these are such as have a wide distribution at the present day. On the other hand, a great number of southern, boreal, and Lusitanian forms had immigrated. The fauna was that of a mild and temperate climate, probably very similar to that of Christiania at the present day. Remains of the oak have been found in the corresponding clay-beds, showing that this forest tree must have been abundant at the period, as was the case when the older Littorina deposits of the Baltic were deposited.

Variation of fauna during the uplift.

A very clear idea of the variations of the fauna of the Christiania region from Yoldia time down to the present day is obtained from the following table, in which the figures are proportions of arctic, boreal, and Lusitanian forms in a total of 48 supposed to represent the whole fauna in each case :

	Arc.	Bor.	Lus.
Present fauna of the Christiania Fjord	6	21	21
Scrobicularia-clay and Lower Tapes-banks	7	19	22
Isocardia-clay and Upper Tapes-banks	7	20	21
Uppermost Ostrea-clay, Ostrea-banks and Uppermost Tapes-banks	8	26	14
Oldest Cardium-clay (Chr.) and Lowest Mya-banks (Smål.)	12 16	25 24	11 8
Mytilus-Cyprina-clay (Chr.) and Lower Mya-banks (Smål.)	24	18	6

	Arc.	Bor.	Lus.
Youngest Arca-clay (Chr.) and Upper Mya-banks (Smål.)	24	21	3
Younger Arca-clay (Chr.) and Uppermost Mya-banks (Smål.)	29	19	0
Middle Arca-clay, etc.	40	8	0
Older Arca-clay and Yoldia-clay	48	0	0

Conclusion as to climate.

The table shows that the climate steadily ameliorated from Yoldia time down to the end of Lower Tapes time, and possibly deteriorated slightly from Tapes time to the present.

Uplift interrupted by small oscillation at Christiania.

We have up to the present described the shell-banks of Christiania from the Uppermost Mya-banks down to the Lower Tapes-banks as deposited during a period of continuous emergence. This, however, requires modification. The more recent investigations of Öyen and Brögger have shown that a definite though small post-glacial submergence took place during Upper Tapes time, when the land lay about 67 metres lower than at present, to the extent of 3 metres, whereby the land sank from its position of 67 metres to 70 metres below its present position. Farther south the amount of submergence was greater, farther north less, so that along a line somewhere in the Mjösensee no submergence can have taken place during this time. North of this zero line the post-glacial emergence was continuous, though no doubt greatly reduced in rapidity during Upper Tapes time. South of the zero line the movement of emergence was interrupted by a retrograde movement, which made itself felt even in Denmark. South of Denmark there is no evidence that the land was at any period of late-glacial or post-glacial time more deeply submerged than at present.

Line of zero oscillation.

Seasonal nature of lamination in Yoldia sediments.

The sediments of the Yoldia Sea in Sweden have been specially studied by De Geer. About twenty-five years ago he put forward the idea that the beautiful lamination of these clays is seasonal, and this conception he has developed in a remarkable manner during the last ten years.[1] The regular alternation of coarse and fine layers is irresistibly suggestive of an annual variation in the sedimentation, the thicker and coarser layers corresponding to the floods produced by the rapid melting of the glaciers in summer, and the thinner and finer layers to the less rapid melting in winter. The annual character of the layers is of course not susceptible of direct proof, but any one who has seen these sediments cannot long remain in doubt on the subject. If the fundamental idea be once granted, then it is clear that we have in these laminae a record not only of the lapse of time during the retreat of the ice, but also a very reliable thermographic record of the late-glacial variations of climate.

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[1] Gerard de Geer, "A Thermographical Record of the Late-Quaternary Climate," in *Die Veränderungen des Klimas*, Geol. Congress, Stockholm, 1910; "A Geochronology of the last 12,000 years," Geol. Congress, 1910.

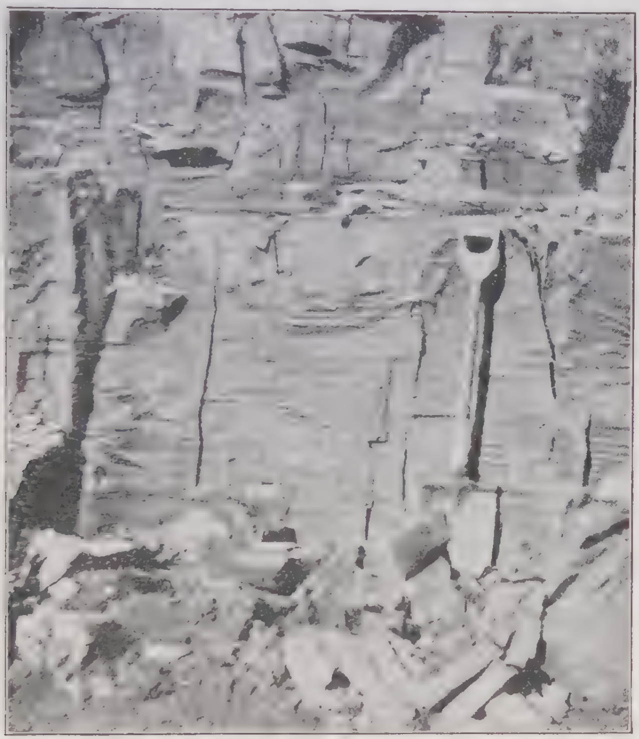

FIG. 115.—Section in the laminated marine clays of Southern Sweden. (From a photograph by Professor Högbom.)

Chronological and climatic record.

It is of course impossible to obtain a single section

Correlation of sections.

showing in superposition all the laminae formed during late-glacial time. De Geer, however, has devised a very ingenious method of getting over this difficulty. By carefully measuring the thicknesses of the annual layers in one locality, and comparing them with the thicknesses at another not very far distant, he has been able to correlate one section with another, and thus build up a continuous series. For this purpose he has made graphs representing the annual variation in thickness. Three of these graphs, representing the lower portions of sections over a kilometre apart, are shown in Fig. 116. The equal intervals measured along the vertical axes represent years, the abscissae the thickness of sediment in the corresponding laminae. On the whole the three graphs show a remarkable correspondence, which is quite sufficient to prove the contemporaneity of the three series of layers.

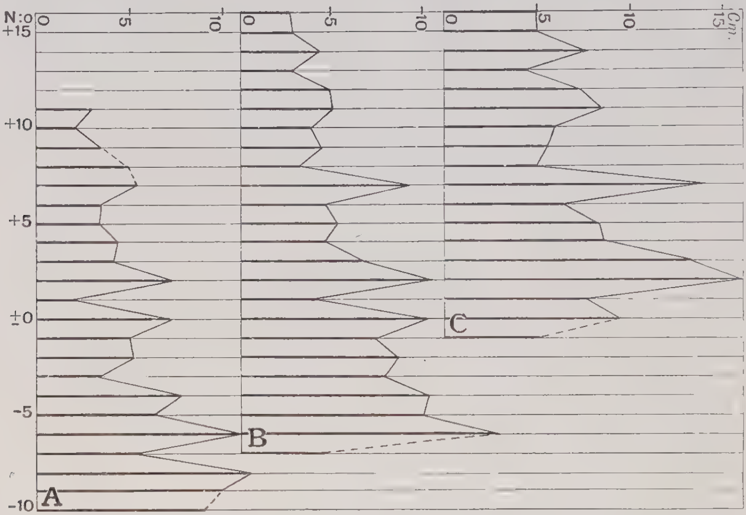

Fig. 116.—Graphs showing the variation in the thickness of the laminae in the late-glacial marine clays of Southern Sweden, and the method of correlating different sections. (After De Geer.)

It will be noticed that there are layers at the base of the section represented by graph A which are not represented in graph B. This means that the locality of the former section was uncovered by the ice and exposed to the sedimentation of the late-glacial sea some years before that of the latter section. In this way De Geer has been able to prove that the intervals between the parallel moraines found in many parts of Southern Sweden represent the annual recession, because, when a series of sections are opened up in the laminated clays deposited between these moraines, a layer is always found to be missing from the bottom of the series when a moraine has been crossed in going north or in whatever direction the ice was retreating. In the Stockholm region the mean annual recession of the ice-margin determined in this manner was about 250 metres. Farther north and nearer the last glacier remnants at the ice-shed the mean annual recession was often as much as 300 or 400 metres.

Annual moraines of Southern Sweden.

Rate of recession.

Sometimes a moraine is found to represent a number of years, and in this manner several well-marked climatic oscillations have been proved. Thus, for example, there are 200 annual layers at the base of the sections outside the great Fennoscandian moraines that are not found inside them. This represents a period of 200 years, during which the ice-margin was readvancing to or standing stationary at the line of these moraines. Immediately succeeding this there was a time of very slow recession, amounting to about 20 metres per year, and lasting for a further 300 years. A period of cold is thus proved, lasting altogether about 500 years, during which the ice probably advanced at first, then stood stationary for a while, and finally withdrew with extreme slowness.

Time-value of the great moraines.

In the same manner De Geer has been able to compute the time occupied in the retreat of the ice-margin from Stockholm to Ragunda in Jemtland. The period arrived at is about 2000 years. At Ragunda there are many beautiful sections in the sediments of the ancient Lake Ragunda, which was completely drained by a catastrophe attending some engineering operations in

Estimate of Late-glacial and Post-glacial Time.

1796. By means of these sections it has been found possible to extend the estimate over post-glacial time. The lake was peculiarly suited to an investigation of this kind on account of its narrowness, which prevented excessive erosion at the margins by wave action and consequent irregularities in sedimentation. It was moreover situated only 50 kilometres east of the ice-shed, and thus was easily influenced by the annual flood caused by the melting of the ice. De Geer has succeeded by the method described above in establishing connexion between several sections situated in sheltered bays away from the main current, and also in finding a complete standard section, 24 metres high, showing the whole sequence of layers from the morainic bottom of the valley through the beautifully laminated characteristic late-glacial clay, and the overlying post-glacial clay marked by numerous black laminae coloured by organic matter and iron sulphide. This clay, which De Geer regards as having been laid down in a post-glacial fjord, passes up into a somewhat more sandy sediment with

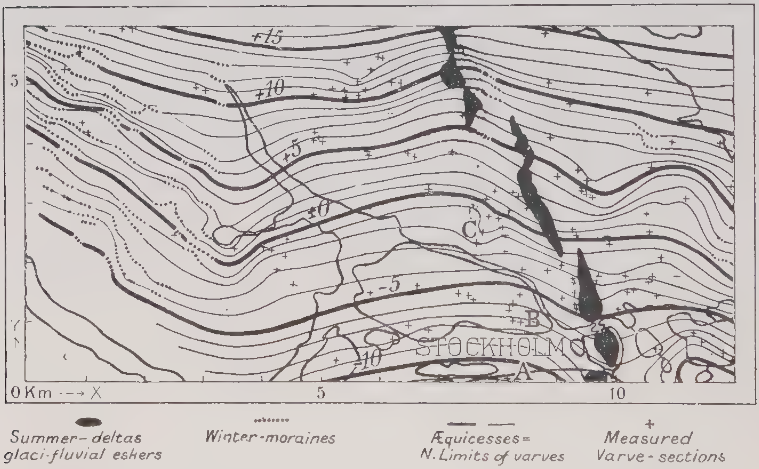

FIG. 117.—Map showing the annual ice-recession in the Stockholm region. The lines, which mark the positions of the ice-margin in successive years, are the northern limits of the varves or laminae in the marine clays. (After De Geer.)

alternating layers of fine silt. The section is uninterrupted all the way up to the surface which formed the ancient lake bottom of 1796. The top, 1·6 metres, has become indistinct through weathering, but it may fairly be assumed that the thickness of the laminae in this portion is on the average the same as that in the immediately subjacent layers. By counting the laminae it was estimated that a period of about 7000 years has elapsed since the ice-margin retreated past this region. This gives altogether 9000 years since the ground on which the University of Stockholm stands first became free from the ice.

De Geer's sub-epochs of retreat and their duration.

The investigation has also been extended into Southern Sweden along a line from Linköping to Kalmar, and from the Kalmar moraine south into Scania. The whole time of retreat De Geer divides into convenient sub-epochs, which are shown in Fig. 118. For the first of these, the Daniglacial, no estimates have been made. The second sub-epoch, the Gotiglacial, during which the ice-margin withdrew from Southern Scania to the great Fennoscandian moraines, was about 2000 years long. The third or Finiglacial Sub-epoch covers the retreat from the great moraines to Ragunda, where the ice-sheet parted into two portions. This period was a little less than 3000 years in length. The bipartition of the ice-sheet is taken as marking the beginning of the Post-glacial Epoch, which is shown by the Ragunda lake-sediments to embrace about 7000 years. This gives in all a period of about 12,000 years, throughout which it has now become possible to date with a fair degree of accuracy any given stage in the retreat of the ice-margin.

Late-glacial history of the Baltic basin.

The late-glacial and post-glacial history of the Baltic basin is even more complex than that of the Atlantic coasts of Scandinavia. During the early stages of the retreat it assumed the character of an ice-dammed lake, the *First Baltic Ice-lake*, which had its outlet to the west by way of the Sound and the Belts. Soon, however, further withdrawal of the ice-margin put it into connexion with the White Sea by a sound extending over the site of Lake Onega. It then entered upon the phase which Munthe has termed the *Zanichellia Sea*. As the

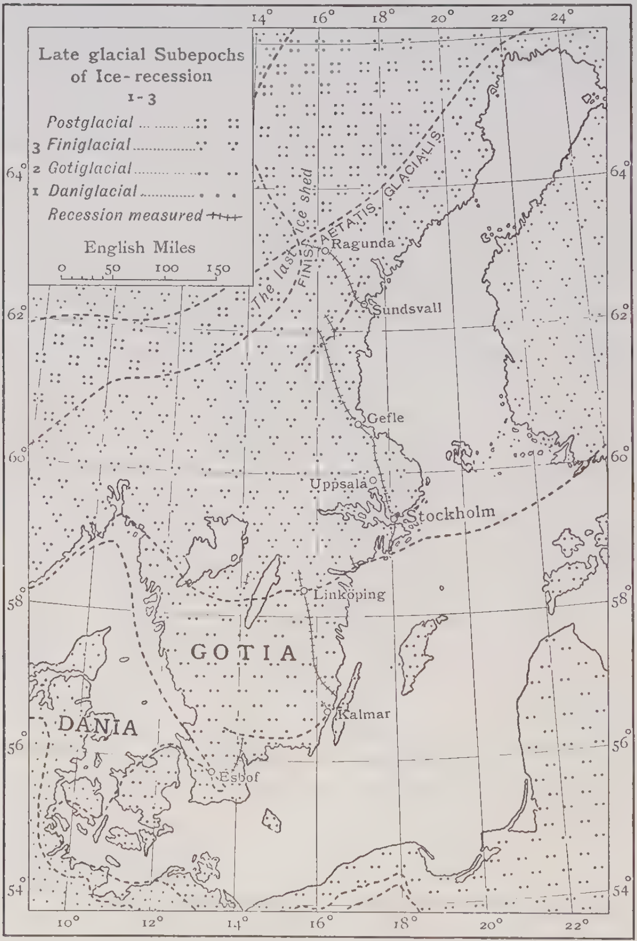

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Fig. 118.—Map of the stages of retreat in Denmark and Sweden. (After De Geer.)

Onega Strait, however, lay near the margin of the area of late-glacial depression, it became elevated at an early stage, in just the same way as the southern portions of the land around the Cattegat recovered from the depression before those lying more to the north (see above, p. 334). This cut off the connexion with the White Sea, and the *Second Baltic Ice-lake* was thus produced. This ice-dammed lake stage was brought to an end by the retreat of the ice from the district of Lakes Wener and Wetter, whereby a connexion with the Atlantic was established across these lakes. This initiated the *Yoldia Sea*, of which some account has already been given above.[1]

Distribution of *Yoldia.*

One of the most interesting points in connexion with the Yoldia Sea is the distribution of Yoldia itself. This arctic species abounded only in the western part of the late-glacial sea, and was much rarer farther east. In fact, the same may be said of nearly all the molluscs of the Yoldia fauna, and there is this marked difference between the stratified clays of Western Sweden on the one hand, and of Eastern Sweden, Finland, and the Baltic provinces on the other, that the former contains a rich fauna of high-northern forms while the latter are almost unfossiliferous. Still more marked is this in the case of the littoral deposits of the Yoldia Sea, which in Western Sweden are for the most part immense heaps of shells. Such shell-banks are, in striking contrast to this, not known to occur at all in Eastern Sweden and the other districts around the Baltic.[2] This is probably, as Erdmann[3] first pointed out, due to the inferior saltness of these eastern parts of the Yoldia Sea, the salt content of which was derived very largely from the Atlantic.

The relict crustacean *Idothea entomon.*

In the deposits of the eastern part of the Yoldia Sea there is found a little White Sea crustacean, *Idothea entomon*, which is completely absent from the western or Atlantic type of these deposits. It is now living in a stunted form in the Baltic Sea, but is not known on the Atlantic coasts of Sweden and Norway. It probably migrated from the Arctic Ocean into the Baltic basin during the Zanichellia stage through the Onega Strait and several other smaller straits which existed farther north at this period.

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[1] Henr. Munthe, "Studier öfver Gottlands senkvartära historia," *Sveriges Geol. Undersökning*, Ser. Ca, No. 4 (1910).

[2] Henr. Munthe, "Om postglaciala aflagringar med *Ancylus fluviatilis* på Gotland," *Öfversikt Kongl. Vetens.-Acad., Förhandlingar*, p. 719 (1887).

[3] A. Erdmann, *Sveriges quartära bildningar*, p. 37. Stockholm, 1868.

Initial rise of sea shown by marginal terraces.

Associated with the moraines of the Vaberg district (see p. 119) are series of marginal terraces (the "Randterrassen" of De Geer). These are flat-topped gravel and sand ridges often 30 or 40 metres high. The southern face is generally a smooth and gentle slope with, locally, a well-marked upper edge. To the east and west the slope is steeper (30 to 35°), and to the north the terrace often runs out into a point or ridge of gravel, the feeding esker. The material is coarsest at the northern or esker end, decreases in coarseness towards the south, and passes rapidly into sand. It seems frequently as if the gravel and sand terraces stood in some connexion with the end-moraines which they border upon, so that each end-moraine has its corresponding marginal terrace and accompanying feeding esker.

These deposits have the characteristic bedding of deltas, and the tops of some of them are as level as a floor. It is remarkable, moreover, that in the Vaberg district they all appear to be at approximately the same altitude, namely, 141 metres over the sea. This shows that they were formed as deltas at the mouths of subglacial streams, which emptied into the sea when it stood at this level, and that this was the level which the sea had attained at the stage of retreat at which these moraines were formed. The highest shore-line of the late-glacial sea in the Vaberg district is 151 metres over the level of the Baltic, so that it is clear that the sea must subsequently have risen another 10 metres. Thus we have in this district an independent demonstration of the fact, first established by Brögger in Christiania, that the sea rose on the land as the glaciers retreated.[1]

This submergence, however, soon reached its maximum, and with the rapid rise of the central portions of Fennoscandia a period of emergence was inaugurated.

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[1] See Herman Hedström, "Om ändmoräner och strandlinier i trakten af Vaberget," *Geol. Fören. i Stockholm, Förhandl.*, Bd. 23, p. 163 (1901).

Production of the Ancylus Lake.

The connexion with the Atlantic across the south of Sweden gradually became constricted, and finally cut off altogether. The history of the Baltic basin then entered upon a new phase. An immense fresh-water lake took the place of the Yoldia Sea. This has been called the *Ancylus Lake* from the little fresh-water mollusc, *Ancylus fluviatilis*, found in its deposits. The first outlet of the lake was across the Wener and Wetter district along the line of the last connexion with the Atlantic in Yoldia times. As the threshold of this outlet was raised by the continuous elevation of the country, the surface of the lake was raised with it, and consequently tended to

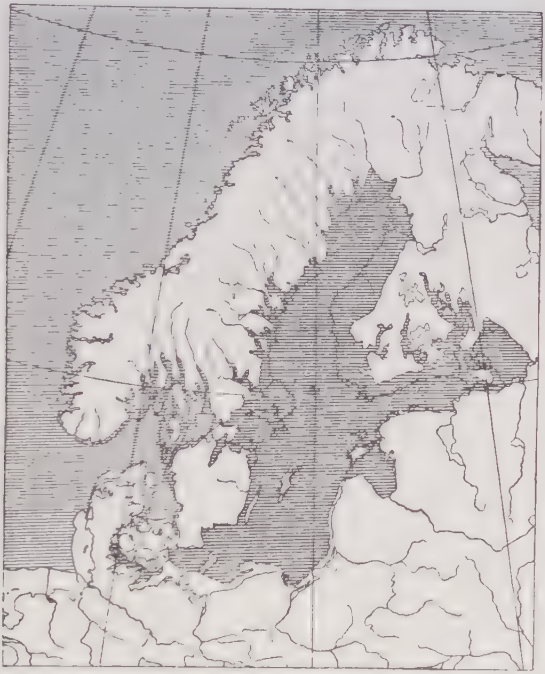

FIG. 119.—Map of the Ancylus Lake.
(From Geinitz, *Das Quartär*, after De Geer.)

The Ancylus transgression.

transgress on the land all around its shores. In the northern part of the Baltic basin, however, no actual transgression took place, because there the elevation of the land went on more rapidly than at the outlet, so that in this region continuous emergence prevailed from the Yoldia maximum on. The rate of elevation at the outlet was, however, greater than the elevation of the land in those parts of the country lying to the south and south-east, so that in these districts the first portion of Ancylus time was a period of progressive submergence. The effect of this is seen in the occurrence in many places of peat beds and lake deposits beneath the gravels of the Ancylus beach. Thus, for example, at Göstafs, in the parish of Fröjel, Gotland, at an altitude of 25 metres over the sea, the following section is recorded :

(*a*)	The uppermost Ancylus beach . .	2·5 -2·8 m.
(*b*)	Marly mud	0·01 ,,
(*c*)	Peat	0·10-0·15 ,,
(*d*)	Marl mud	0·30-0·40 ,,
(*e*)	Clay with sand and gravel . . .	0·10-0·15 ,,
(*f*)	Boulder-marl.	

Climate during the pre-Ancylus emergence in the South Baltic.

The bed (*e*) contains arctic plants, including *Salix polaris*, *Arctostaphylos alpina*, *Dryas octopetala*, *Betula nana*, and *Zanichellia polycarpa*, and arctic molluscs such as *Planorbis arcticus* and *Pisidium lovéni*. The occurrence of these forms beneath the gravels of the Ancylus Lake shows that of the total emergence of 85 metres, which has taken place in Gotland since the Yoldia maximum, some 70 per cent was accomplished while an arctic flora and fauna were flourishing in the vicinity.[1] In Scania (Southern Sweden) remains of *Salix polaris* have been found in fresh-water clays close to the present sea-level, showing that the land had reached at least its present level relatively to the sea at a time when the climate was still arctic.[2] These important observations show the rapidity of the late-glacial recovery in these peripheral parts of the depressed area. Then with the disappearance of the arctic flora and fauna came the Ancylus transgression due to the raising of the outlet. While this transgression was in progress, Southern Scania was connected with Zealand and Denmark by a belt of dry land, and across this bridge there entered many elements of the present fauna and flora of Scandinavia. The low-water level in the southern part of the Baltic during the Ancylus stage is shown by the submerged peat mosses which occur here. About a third of a mile south of Falsterbo there is out at sea a great submerged peat moss, some 10 to 12 feet thick, bearing oak trees in its upper part. The surface of the peat now lies, according to Nillson, 14 feet beneath the present sea-level. Close to the shore at Pillau, in the Gulf of Danzig, fresh-water beds have been found at a depth of 30 metres, thus lying a considerable distance below sea-level.[1]

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[1] Henr. Munthe, "Studier öfver Gottlands senkvartära historia," *Sveriges Geol. Undersökning*, Ser. Ca, No. 4, p. 184 (1910).

[2] Gunnar Andersson, *Svenska Växtvärldens historia* Stockholm, 1896.

Transference of the outlet and maximum of transgression.

In the course of time, however, the progressive tilling of the land transferred the outlet to the Sound and Belts, which must at that period have lain well above the level of the ocean. At the stage of balance between the two outlets occurred the maximum transgression of the Ancylus Lake in the south of the Baltic basin.[2] The warping which took place after the establishment of the southern outlet caused emergence in all districts north of the isobase of this outlet. This was the late Ancylus period, which followed upon the Ancylus maximum. It was brought to an end by the submergence of the Sound and Belts during the so-called Tapes depression of the southern Christiania Region (see p. 338).

Initiation of the Littorina Sea.

The Littorina transgression.

When communication had thus been re-established with the ocean the Baltic entered upon the Littorina stage. The change was accompanied by a renewed tendency to transgression within the Baltic basin. This had no effect in the north since the land was there still rapidly rising, but in the south its effect is apparent in the occurrence of peat between the Littorina and Ancylus deposits, as for example in Gotland (see Fig. 120). This transgression, however, soon reached a maximum, and the continuous elevation of the land once more made itself felt, and from that on emergence has proceeded without interruption to the present day.

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[1] *Zeitschr. der Deutsch. Geol. Gesellsch.* Bd. 42, p. 618 (1890).

[2] Except, perhaps, over a small area, now below sea-level, which lay to the south of the isobase of the southern outlet.

Oscillation of sea-level in Gotland.

The admirable researches of Munthe on the island of Gotland have made it classic ground in the study of the post-glacial oscillations of the Baltic. It will therefore not be amiss to summarise here the leading events in its complex history. At the time of the Yoldia Sea the island, the highest point of which lies only 80 metres over the sea, was completely submerged. Then followed rapid emergence until the shore-line stood not more than 25 metres over the sea. There was then a submergence in the same district to an altitude of 29 metres, the Ancylus maximum, followed by emergence, bringing the shore-line to a relatively low level. As a result of the ingress of the sea in Littorina times there was then a renewed submergence to an altitude of 18 metres, and lastly a period of emergence extending to the present day. The figures given are for the district of Fröjel, about the middle of the west coast of the island, but it must, of course, be understood that they will be greater in the north end of the island and less in the south, as all the shore-lines rise northward. Thus in the

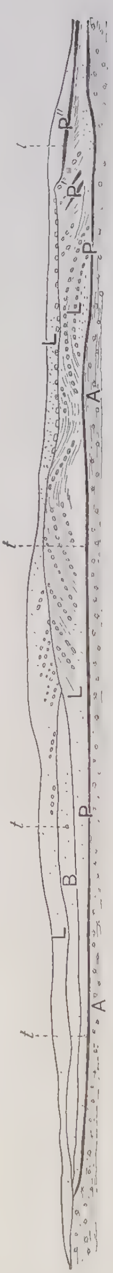

Fig. 120.—Section through a shore rampart of the Littorina Sea at Snoder in Gotland, showing the Littorina gravel (L) separated from the Ancylus gravel (A) by an extensive peat bed (P) with tree stumps (*tt*). (After L. von Post.)

B is blown sand. P′ P″ are peat beds in the Littorina gravel, which is subdivided into an upper and lower series by these deposits.

extreme south of the island the Ancylus maximum was only 19 metres, and the Littorina maximum 14 metres, while at the north end the figures were respectively 45 metres and 24 metres.

Indefiniteness of North Baltic shore-lines.

There is a very great difference in the development of the Ancylus and Littorina shore-lines in the north and south of the Baltic. In the north they can only be traced with difficulty, while in the south they are well marked and striking. This is obviously due to the fact, pointed out above, that in the north they were formed during a mere slowing down in the continuous emergence, whereas in the south they record periods at the climax of each transgression during which the sea stood for a relatively long period at a constant level on the land.

Significance of submergence of the Ancylus outlet.

On the south coast of Scania, and generally in the extreme south of the Baltic, the Ancylus deposits lie entirely beneath sea-level. Passing north, they first appear for certain at Nosaby, and here and in western Bleking they occur just above sea-level. Thence northward they rise steadily to greater and greater altitudes above the sea.[1] The submergence of the Ancylus outlet and the southern portions of the Ancylus shore-line is one of the most significant facts in connexion with the history of the Baltic. It admits of but two explanations: there must either have been an elevation in the region of the Sound and Belts during Ancylus time, or else the general level of the ocean outside must have been considerably lower. We shall show later, in connexion with the submerged forests of North-western Europe, that the latter is almost certainly the correct explanation.

Salinity of the Littorina Sea.

During Littorina times the waters of the Baltic were much salter than now, and certain molluscs, which are at present confined to its lower reaches just inside the Belts, extended inwards to a much greater distance. On the assumption that the greater inward range is due almost entirely to this greater salinity, and not at all, or only to a minor extent, to other causes, Doctor

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[1] Nils Olof Holst, "Östersjöns och Bottinska Vikens Postglaciali Geologi," *Sveriges Geologiska Undersökning*, Ser. C, No. 180. Stockholm, 1899.

Munthe[1] has drawn a comparison between the salinity of the various parts of the Baltic in Littorina and present times. The results of his investigations are shown in Fig. 121, on which are drawn isohalinic lines or curves of equal saltness for both periods. At every point on one of the curves, shown as a continuous line, the sea has at the present day a degree of salinity represented by the figures attached to that curve, and at every point on one of the interrupted curves the sea had in Littorina times the salinity indicated by the figures attached to it. Thus, for example, at the present day we find water containing as much as 0·8 per cent of salt only to the west of Rügen along the curve indicated by the figures 0·8, whereas in Littorina time as great a salinity occurred in the extreme north of the Gulf of Bothnia along the interrupted curve to which the same figures 0·8 are attached.

Explanation of the greater salinity.

The cause of this greater salinity is, however, not so obvious, for the connexion with the Cattegat was not then to any appreciable extent more open than it is now. The land in the region of the Belts stood at almost exactly the same level as at the present day, and the "threshold" in the south part of the Sound was at that time only 5 metres lower than now. Other factors were at work, however. The sea immediately outside in the Cattegat itself was for one thing much salter. This has been shown by the study of the fauna of Littorina times in this region, and is due, as De Geer pointed out, to the submergence of the northern part of Denmark permitting the freer access of the Gulf Stream. Another and probably much more potent cause lies, however, as suggested by Munthe, in the depth of the Littorina Sea itself, which was considerably greater than that of the present Baltic. In this deeper sea the under-currents of heavy salt water were much less interfered with by banks and shoals, and could penetrate much farther in.

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[1] Henr. Munthe, "Preliminary Report on the Physical Geography of the Littorina Sea," *Bulletin of the Geological Institute of the University of Upsala*, vol. ii. p. 1 (1895).

Warping of the Littorina shore-line.

The relative shallowness of the recent sea is due, of course, to the post-Littorina elevation of the central districts of Fennoscandia. As we pass north along the

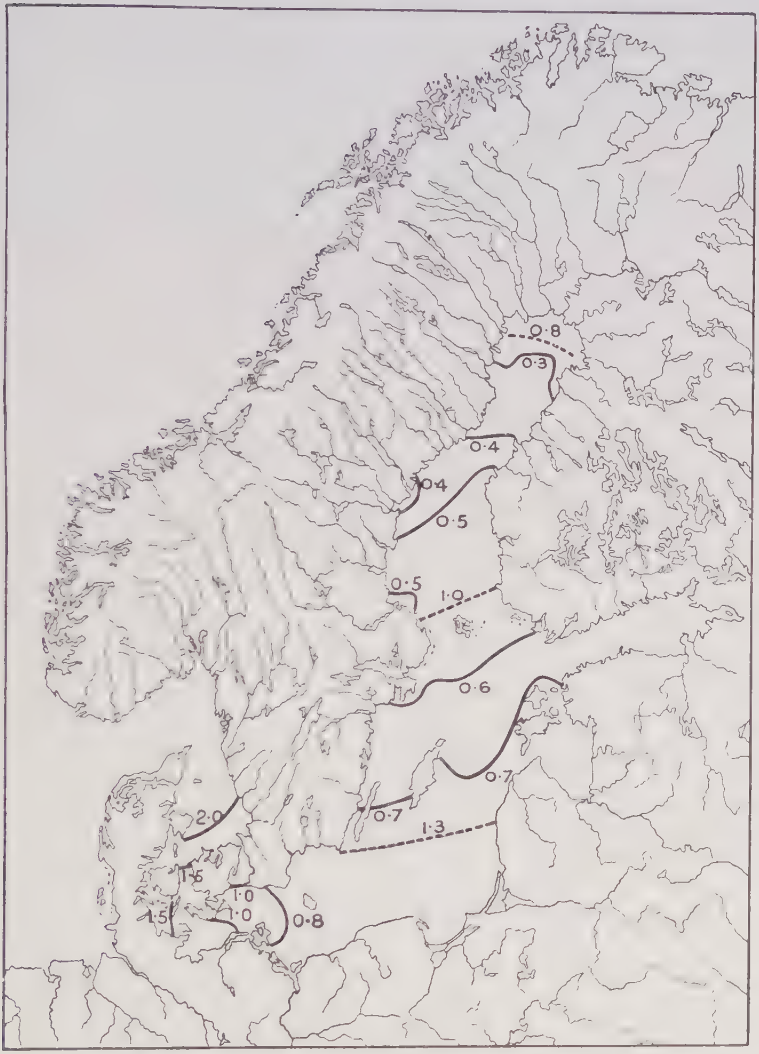

Fig. 121.—Map of the Baltic showing the isohalinic lines at the present day and in Littorina times. (After Munthe.)

Baltic coast of Sweden, the deposits of the Littorina Sea occur at higher and higher levels. Thus, in the neighbourhood of Stockholm they are found some 60 metres above the present sea-level, and in the Gulf of Bothnia they rise as high as 100 metres. This elevation is graphically represented in Plate XIX., on which are drawn the isobases or curves of equal post-Littorina elevation. For example, all shore deposits of the Littorina Sea lying on the curve marked 60 have been elevated 60 metres since Littorina times, and so on. In this plate is also shown the extent to which the Littorina Sea encroached on the land round the shores of the Baltic.

Northward increase of gradient.

When traced into the Christiania region the Littorina deposits are easily seen to be the equivalent of the Tapes banks of Brögger (see p. 334). A glance at the map will show that the zero isobase[1] passes through the middle of Denmark. South of this the land has been sinking relatively to the sea in post-Littorina times; north of it, it has been rising, and the amount of elevation increases progressively northwards, reaching in the Christiania region as much as 70 or 80 metres. It will be also noticed that the gradient becomes steeper towards the north, the Littorina shore-lines rising, as pointed out by Brögger, in a sort of parabolic curve. The average gradients are as follows :—

From the zero line to the N.E. point of Jutland .	1 m. in 10 km.
Between Fredrikshavn and Hvaler (Christiania-fjord) .	1 m. in 7 km.
Between Hvaler and Christiania	1 m. in 3·5 km.

The Campignien kitchen-middens.

In connexion with the general submergence in post-glacial time in the area south of the zero isobase, a remarkably interesting fact has been brought to light by Holst[2] regarding the kitchen-middens which occur at intervals along the coast from Northern France to Jutland. These are of Campignien age (see p. 284). The peculiar hatchet-shaped implements characteristic of this period

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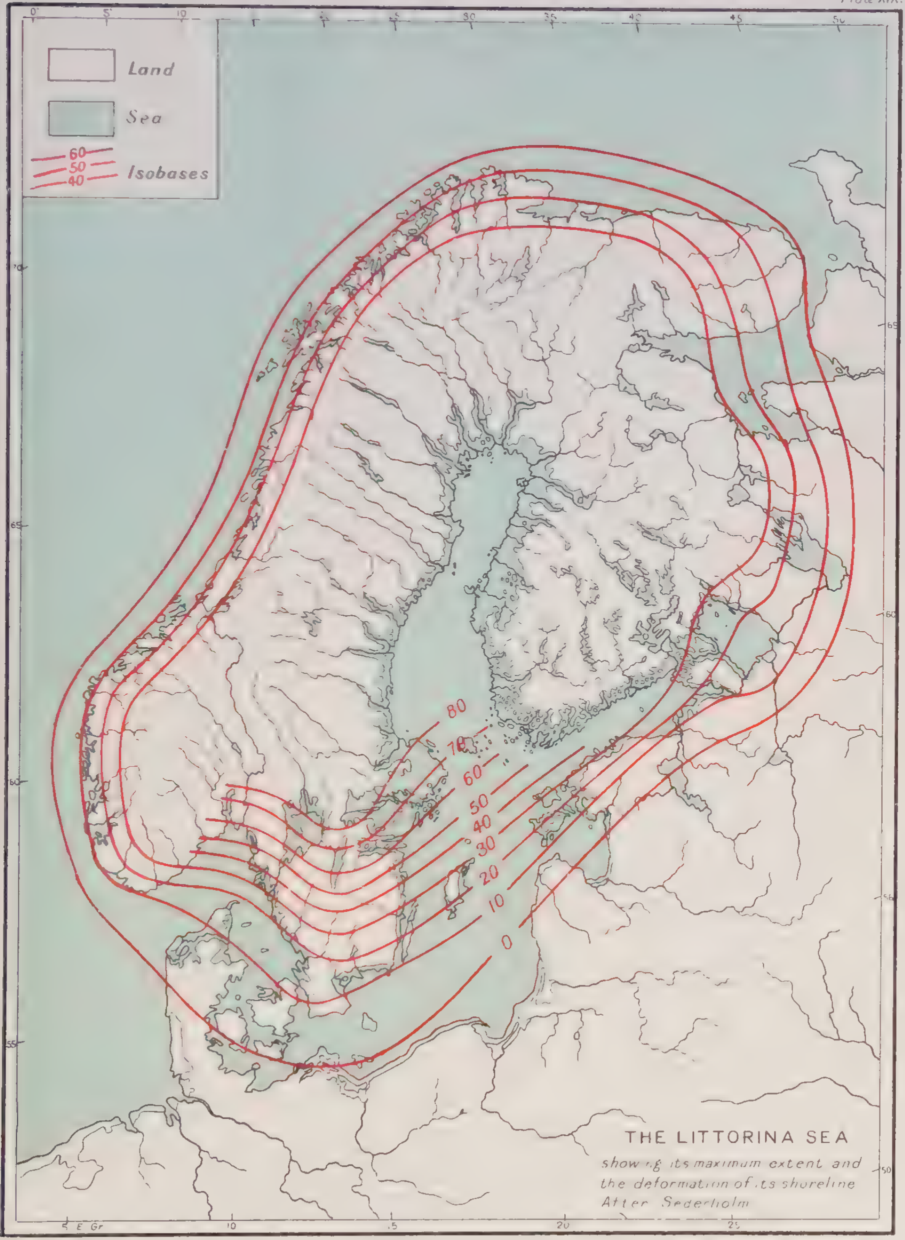
[1] Not to be confused with the line of zero movement during the Littorina-Tapes submergence. See p. 338.

[2] N. O. Holst, "Kvartär-studier i Danmark och norra Tyskland," *Geol. Förenigens i Stockholm, Förhandlingar*, vol. xxvi. p. 433 (1904).



THE LITTORINA SEA

showing its maximum extent and the deformation of its shoreline After Sederholm

To face p. 354]

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(Fr. *grands tranchets*, Norwegian *skivespalter*) have been traced from Northern Italy, through France (where they are known as the Campignien type) into Belgium, and along the coast of the North Sea to Denmark and Scandinavia. They probably mark the track of the northward migration of the Early Neolithic people. These people, apparently, lived mainly on the sea-coast, subsisting largely on shell-fish, and building the great rubbish-heaps or "kitchen-middens" in which their implements are now found. In Northern Jutland these kitchen-middens all occur on the highest strand-lines of Littorina time, and lie at some distance from the present shore. Passing south along the coast of Denmark they approach the present sea-level, sinking with the Littorina shore-line until, in Southern Jutland and Schleswig-Holstein, they disappeared altogether, and are not found again any nearer than the coast of Belgium. Holst perceived that the kitchen-middens had undoubtedly been formed along these coasts, and that their apparent absence is due merely to their being submerged beneath the sea. He obtained remarkable confirmation of this in several instances. Thus at Koldingfjord a number of stone and bone implements of Campignien age were dredged up from a depth of 3 or 4 metres. In Kiel harbour some objects regarded as belonging to a kitchen-midden were found during dredging operations. These included shells, instruments made of stag-horn, bones of the stag, urox, and so on. We can recognise in this submergence of the Campignien remains the effects of the general post-glacial rise of the sea in the districts outside the Scandinavian area of post-glacial elevation, the effect being perhaps heightened in the neighbourhood of Holland by a local isostatic effect (see p. 406) due to the enormous quantities of sediment accumulated here.

Their submergence south of the zero isobase.

By recent Danish and Swedish researches it has been determined that the time of the older Danish kitchen-middens which contain the *skivespalter* corresponds to the time of the maximum post-glacial Littorina-Tapes submergence. Investigation of dwelling-places at

Date of the Danish and Swedish *skivespalter.*

Copenhagen, on Fünen, and at Järavallen in Schonen, has proved, however, that *skivespalter* were in use at an earlier time, namely, the latter part of Ancylus time. They were, however, of an imperfect type and by no means abundant, and there is clearly a development from the rougher type of Ancylus time to the perfect type of Littorina time. The climate, however, even at the time of the earlier type of Danish *skivespalter*, was not any colder than at present.

Date of the Norwegian *skive-spalter*.

Skivespalter have been traced into Norway and Sweden, but they are by no means abundant there. Most of the finds correspond fairly well with the strand-line of the maximum of the Littorina-Tapes depression. A few are found below it. None are ever associated with higher strand-lines. The manufacture of *skivespalter* in Norway was confined to Littorina-Tapes time. It continued for some time after the maximum depression, but if there were any inhabitants of Norway before this time, they were incapable of manufacturing these implements.[1]

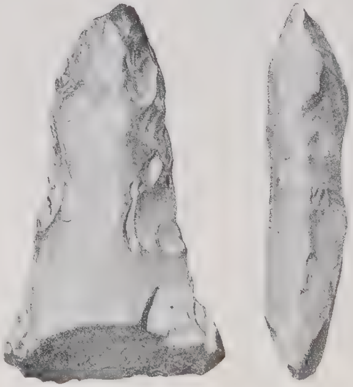

FIG. 122.—*Skivespalter* or *grand tranchet* of flint from Grue in Hedemarken, Norway. (About $\frac{2}{5}$ natural size, after Brögger.)

Relation of Campignien and Neolithic implements to the shore-lines.

The relation of the various phases of Neolithic culture to the stages of recovery from the Littorina-Tapes depression has been the subject of a piece of work by Brögger, which has no parallel for beauty and precision in the annals of archaeology. Neolithic man lived, in his earlier stages, mainly by hunting and fishing. His dwelling-places are therefore found grouped to a certain extent along the shore-line of his time. This enables a very exact correlation to be made between the earlier types of implement and the level of the sea at the time they were manufactured. At a later date pastoral and agricultural habits of life were gradually adopted, and the association of the later types with the corresponding shore-line is not so well marked. It can be shown, however, that even in these cases there is a distinct limit below which certain types of implement do not occur. In this manner it has been possible to trace the development of the well-known Neolithic axe-head or celt from its rough-hewn primitive form down to the delicately fashioned type which preceded the introduction of metals.

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[1] W. C. Brögger, "Strandliniens Beliggenhed under Stenalderen," *Norges Geologiska Undersögelse.*

Sub-division of Tapes- and post-Tapes time.

For the purpose of comparison with these stages of Neolithic culture, Brögger has distinguished the following subdivisions of the period between the maximum of the Littorina-Tapes depression and the present day:[1]

(1) Older Tapes Time.

Corresponding to the recovery of the land at Christiania from a position 70 metres to one 45 to 48 metres below its present level. Climate as shown by the fauna, mild, with August temperature about $2\frac{1}{4}$° C. higher than at present. Shell-banks with southern forms (*e.g.* *Tapes decussatus*, L., and *Pholas candida*, L., both subsequently vanished from the fjord). Corresponding clay the older part of the Isocardia clay.

(2) Middle Tapes Time.

Corresponding to the recovery of the land at Christiania from a position 45 metres to one 19 to 21 metres below its present level. Climate somewhat colder than during Older Tapes Time, probably also somewhat colder than during Younger Tapes Time. Corresponding clay the younger part of the Isocardia clay.

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[1] W. C. Brögger, "Strandliniens Beliggenhed under Stenalderen," *Norges Geologiska Undersögelse.*

(3) Younger Tapes Time.

Corresponding to the recovery of the land at Christiania from a position 19 metres to one 8 to 10 metres below present level. Climate mild, warmer than at present. Shell-banks characterised by a considerable number of southerly forms now vanished from the fjord. Corresponding clay the Scrobicularia clay.

(4) Recent Time.

Corresponding to the recovery of the land at Christiania from a position 8 metres below its present level to the present level. First indication of a climate similar to the present and arrival of *Mya arenaria*, L.

Axes characteristic of the Tapes maximum.

The oldest phase of the Stone Age culture in Norway is that known as the Nöstvet culture. It is characterised by rough-hewn stone axes of the type shown in Fig. 123. A few of the dwelling-places of this period occur at higher levels than the strand-line of the Littorina-Tapes Maximum, but the greater number exactly correspond with it. None have ever been found below the level of this strand-line. The Nöstvet culture in Norway was thus contemporaneous with the kitchen-midden period in Denmark from which it clearly sprang, the Nöstvet men merely seeking in other fine-grained stones a substitute for flint. In the earlier stages of this period, which is Brögger's "Older Northern Stone Age," the axe-heads were simply roughly hewn into shape, but later an improvement was introduced in the nature of polishing of the cutting edge. It was not, however, till the next succeeding period, when the sea had already abandoned the shore-line of the Littorina-Tapes Maximum, that the primitive process of hewing was abandoned, and flaking combined with polishing introduced in its place. This decided advance in the method of manufacture was, according to Brögger, almost certainly imported, and came to Norway from Western Europe.

The second period, which is Brögger's "Northern

Axes characteristic of the end of Older Tapes Time.

Transitional Stone Age,” is characterised by stump-necked round axes (*butnakkede trindöxer*) of the type shown in Fig. 124. They are known from about 150 localities, 65 of which have levels considerably higher than the strand-line which corresponds to the last part of Older Tapes Time. About half of these high-lying localities are situated on lake margins. Of the remaining 80 or so low-lying localities, not a single one has with certainty as low a level as the above-mentioned lowest strand-line of Older Tapes Time. The manufacture of these implements must therefore have ceased before the end of Older Tapes Time: and since they are never found in the same dwelling-places as the Nöstvet type, the manufacture of one must therefore have ceased before the other began. The chronological boundary between the two types is the Littorina-Tapes Maximum.

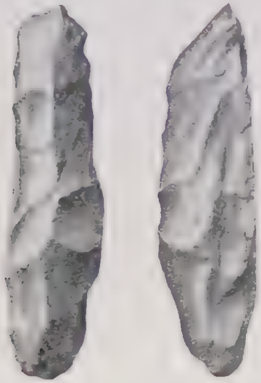

Fig. 123.—Stone axe of Nöstvet type from the great dwelling-place at Torp in Jarlsberg, Norway. (About ⅓ natural size, after Brögger.)

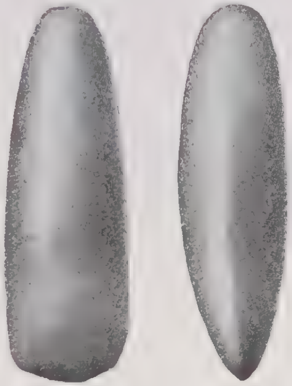

Fig. 124.—Stump-necked round axe from Torp. (About ⅓ natural size, after Brögger.)

The dwelling-places of the Nöstvet culture are characterised by large numbers of implements, as many as two or three hundred in each of the larger ones. Those in which the stump-necked axes are found, on the other hand, yield only a few implements each. These latter dwelling-places are, however, much more numerous, and occur over a much wider area. The people of the stump-necked axes were obviously more nomadic in their habits.

With the commencement of Brögger's "Younger Northern Stone Age," or time of polished stone axes proper, the manner of life of the people became more and more pastoral and agricultural, and their dwelling-places were no longer confined to the shore. An exact determination of the position of the shore-line such as has been made in the case of the Older and Transitional Stone Ages is therefore no longer possible. By taking, however, the lowest positions of the Younger Stone Age implements, Brögger has obtained an upper limit which is at least an approximation to the true position.

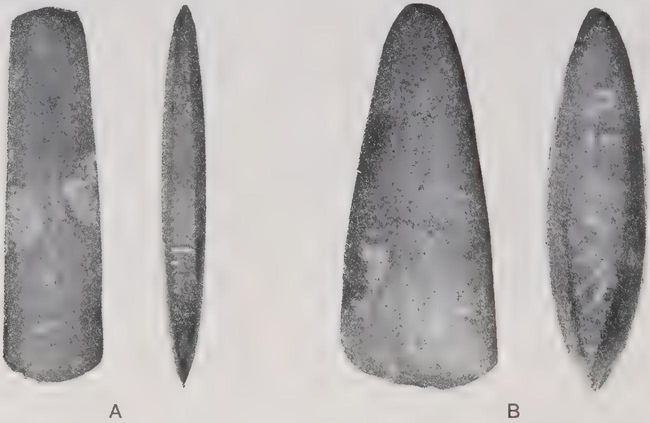

Fig. 125.—A, Thin-necked axe of flint from Skoro, in Akershus, Norway. (About $\frac{1}{5}$ natural size.) B, Point-necked axe of greenstone from Drangedal, Bratsberg, Norway. (About $\frac{1}{3}$ natural size, after Brögger.)

Axes characteristic of Middle Tapes Time.

The axes of the Younger Stone Age take several forms, of which the thin-necked axe (Fig. 125), the thick-necked axe (Fig. 126), and the shaft-hole axe (Fig. 126) are the most noteworthy. Consideration of the low-lying localities of thin-necked stone and flint axes show that they do not occur at Christiania lower than 23-26 metres, and at the mouth of the fjord lower than 18-20 metres above sea-level.

Axes characteristic of Younger Tapes Time.

The thick-necked axes and shaft-hole axes, on the contrary, go considerably lower, showing that the position of the strand-line at Christiania at the end of the Youngest Stone Age must have been only about 13-15 metres higher than at present. This result has been confirmed by the finding of instruments of this age in the Scrobicularia clay of the Christiania valley, and by the occurrence of graves of the Younger Stone Age in Drammensfjord, and at Jarlsberg at a height of about 20 metres over the sea. These and similar determinations in other localities prove the following variations from place to place in the level of the strand-line of the Youngest Stone Age:

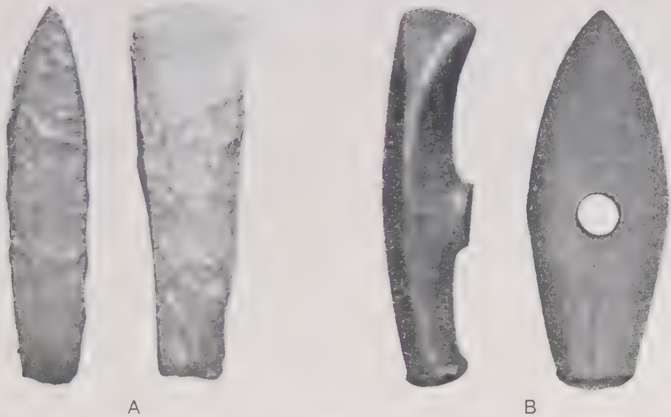

Fig. 126.—A, Thick-necked axe of flint from Naesodden, Akershus, Norway. (About $\frac{2}{7}$ natural size.) B, Boat-shaped shaft-hole axe from Sannergaden, Christiania. (About $\frac{1}{3}$ natural size, after Brögger.)

At Kristiania	13-15 m. above sea-level.
At Svelirk and in Sande	12-14 ,, ,, ,,
In Ramnaes, Slayen, Rugge, and Råde .	11-13 ,, ,, ,,
In Tjölling, Brimlaues, Onsö, and Skjeberg .	9-11 ,, ,, ,,

The Bronze Age.

The only fact of value with regard to the Bronze Age is the existence of a cairn of this period at Slagen, near Tönsberg, on the Christiania fjord, which shows that the sea at that spot at the end of the Older Bronze Age cannot have been more than 3 to 5 metres higher than at present. At the end of the Bronze Age the elevation of the land was probably completed.

The Vin-colonisation.

The oldest names of farms in Norway are, as was first proved by Professor O. Rygh, associated with the word Vin (= pasture land). By a comparison of the distribution of the Vin-names in the larger valleys with that of the instruments of the Younger Stone Age, Brögger has been able to show that the Vin-colonisation took place in South-east Norway about the beginning of the Youngest Stone Age (the time of the thick-necked and shaft-hole axes), when the strand-line at Christiania was at a height of about 25 metres above its present level.

Summary.

The following table summarises the position of the strand-lines at the various stages:—

CORRELATION OF THE SEA-LEVEL IN SOUTHERN NORWAY WITH THE TYPES OF CAMPIGNIEN AND NEOLITHIC IMPLEMENTS

	At Christiania.	At Fjord Mouth.
At end of Older Stone Age (Nöstvet axe)	70 m.	42 m.
At end of Middle Stone Age (stump-necked round axe)	50 m.	36 m.
At end of older part of Younger Stone Age (thin-necked and point-necked axes)	25 m.	19 m.
At end of Youngest Stone Age (shaft-hole axe and thick-necked axe)	15 m.	about 10 m.
At end of Bronze Age	0 m. (?)	0 m.

CHAPTER XVI

RAISED BEACHES AND SUBMERGED FORESTS OF THE BRITISH ISLES

Sea-level in preglacial times—Subsequent emergence—Fragmentary nature of the evidence regarding the glacial sea-level—Late glacial submergence of Scotland—The 100-foot beach—Jamieson's investigation of the marine clays—Relation of the 100-foot beach to the Moraine Glaciation of the Highlands—Anomalies in the distribution of the 100-foot beach of Scotland—The 50-foot beach of Scotland—The submerged forests—The Pentuan stream-tin section—The Barry Dock section—The Hull section—Wide distribution of the submerged forests—Relation to the Ancylus Lake—The post-glacial 25-foot beach—Relation of the submerged forests to the post-glacial and late-glacial periods of submergence—The Alexandra Dock section at Belfast and the Larne raised beach—Relative motion of land and sea—Importance of the 25-foot beach—Its distribution, deformation, and fauna—The associated estuarine deposits—Its early Neolithic or Campignien age—The Larne gravel-spit—Other cases where Neolithic remains can be seen in relation to the 25-foot beach.

Investigations into the post-glacial history of the British Isles have to a very large extent been concerned with the remarkable oscillations of the relative level of land and sea which characterised this period. With regard to these more recent oscillations we possess, indeed, a very considerable amount of information; and although still faced by many unsolved problems, we are dealing here with a record which is almost an open book to us in comparison with that of the immediately preceding Glacial Period. The reader who has studied with care the preceding pages will perhaps have remarked how little reference is made therein to the position of the sea-level during the Ice Age. If I have conveyed

Sea-level in preglacial times.

Subsequent emergence.

Possible extent of this emergence.

to him by this reluctance to discuss the matter any idea of the state of our ignorance concerning it, I have accomplished almost all that is at present possible. There are, however, a few exceptions to this which he will scarcely have failed to take note of. One of the most important of these is undoubtedly the very exact knowledge we possess of the position of the shore-line of a great part of the British Isles and the adjoining coast of France immediately before the Ice Age. It has been demonstrated in Chapter V. that for a fairly prolonged period of preglacial time the sea-level differed little from that of the present day. Cold conditions of sufficient severity for the existence of floating ice in the English Channel had, moreover, set in before it abandoned this level. The subsequent displacement was, it will be remembered, one of elevation of the land, or as I would prefer to express it on theoretical grounds, of depression of the sea-level. How far this depression proceeded it is impossible to say. We possess certain isolated and by no means unassailable scraps of evidence that it was very considerable. Thus, for example, from the enormous depth of 2600 metres in the Norwegian Sea, high arctic shallow water mollusca of the Yoldia fauna have been brought up in dredges,[1] and there are other traces of shallow water or land conditions on this shelf.[2] Very little, however, is at present known regarding this elevation, and it is not at all clear that it was continuous and uninterrupted by periods of submergence. We have in this connexion to take account not only of such deposits as the remarkable interglacial shell-bed at Kirmington (see p. 79), but even of the still more enigmatical shell-beds interbedded and incorporated in the drifts of the Clyde basin, Clava, and Campbelltown in Scotland.[3] Certain remnants of raised beaches in the south of England, as for example the March gravels[1] in the Fens, and the Goodwood Beach[2] in Sussex, may also have a bearing on this question. The whole problem is, however, so beset with difficulties that it could not be discussed adequately within the limits prescribed in the present volume, and we shall therefore pass on to the consideration of a series of events about which we have considerably clearer evidence.

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[1] W. C. Brögger, "Om de senglaciale og post-glaciale nivåforandringer i Kristianiafeltet," *Norges Geologiska Undersögelse*, No. 31, p. 682 (1901).

[2] *Ibid.* p. 683.

[3] On this subject see *Rep. Brit. Assoc.*, 1893, p. 483; 1894, p. 337; 1896, p. 378; *Geol. Mag.*, 1895, pp. 277, 322, 351; 1896, p. 498; 1897, pp. 27, 63.

We have seen in the last chapter that on the final decay of the Scandinavian Ice-sheet, the sea invaded an extensive district round about the centre of dispersion. This sea, the Yoldia Sea, possessed an arctic fauna and coexisted with the retreating glaciers. Now it is a remarkable and significant fact that this late glacial submergence has its counterpart around the Scottish centre. There is abundant evidence that, while the Highlands were still buried in ice and great glaciers occupied many of the fjords, the surrounding districts were submerged to a somewhat greater extent than at the present day. This submergence was small in amount compared to that which affected Scandinavia and Finland. It attained at most about 100 feet, and affected, as far as we know, a relatively limited area. It has left its record in a more or less distinctly marked raised beach, the 100-foot beach of Scotland, and in certain locally developed deeper water clays. These latter have been studied with remarkable insight and care by Mr. Jamieson, who, in his masterly paper "On the History of the Last Geological Changes in Scotland,"[3] published in the year 1865, assigned them to their proper place in the geological sequence, and brought out many interesting points concerning them. The clays are well exposed, or were formerly well exposed in pits at Errol, between Perth and Dundee, at Portobello near Edinburgh, at Paisley and Renfrew on the Clyde, at Kilchattan in

The late glacial submergence of Scotland.

The deep-water clays of the 100-foot period.

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[1] See S. B. J. Skertchly, "The Geology of the Fenland," *Mem. Geol. Surv. of England and Wales* (1877), where other references are given; also A. J. Jukes-Browne, "On the Southerly Extension of the Hessle Boulder-clay in Lincolnshire," *Quart. Journ. Geol. Soc.* vol. xxxv. p. 416 (1879).

[2] See Clement Reid, "The Geology of the Country near Chichester," *Mem. Geol. Survey of England and Wales*, p. 40 (1903), where other references are given.

[3] *Quart. Journ. Geol. Soc.* vol. xxi. p. 161 (1865).

Bute, and at Benderloch in Argyll. The Paisley section is perhaps the most instructive. The clay, which is here used for brick-making, has its surface about 40 feet above sea-level. It is a finely laminated tenacious mud, abounding in shells of arctic type. Many of these have the valves still united, and are obviously in the position in which they grew. The extreme delicacy of some of the species, and the perfect manner in which even the epidermis is preserved, necessitate the same conclusion. All the indications point to quiet deposition in fairly deep water, on the muddy bottom of which flourished an abundant molluscan fauna.

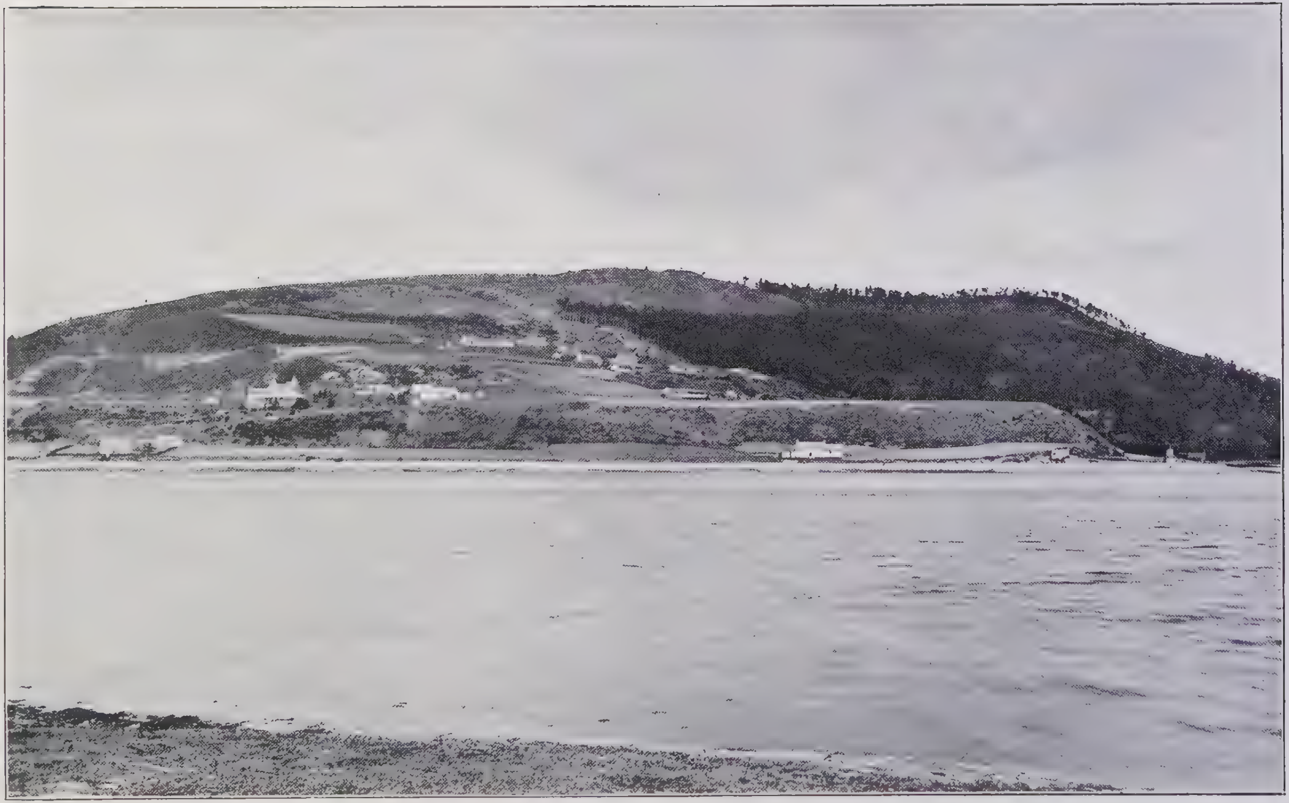
Their arctic fauna.

Other evidence of the arctic character of the 100-foot sea.

The arctic character of this fauna is in itself conclusive proof that the clays are of glacial age. They possess, however, another feature no less significant in this respect. Throughout the section, boulders of all sizes up to 3 feet in diameter are fairly common. Jamieson observed one 6 feet in length. Many of them show glacial striae. They occur embedded here and there at various depths in the fine clay, sometimes singly, but frequently one or two together. It must be conceded that the presence of these heavy boulders in the midst of a delicately laminated marine silt, far from any high ground whence they could have rolled down, is conclusive proof of the existence of floating ice.

Now, it is quite a common thing to find the upper surfaces of these boulders overgrown with a crust of Balani or acorn shells. In most cases, if the mud be cleared away from the sides of the boulder, the Balanus growth will be found to cease abruptly along a horizontal line running round it. This marks the extent to which the boulder was embedded when the Balani grew on it, and shows that it had been dropped into its present position before the growth took place. Jamieson, however, has pointed out that the Balani are not always confined to the upper surface and sides of the stone. For example, he observed one heavy stone measuring 32 × 18 × 14 inches embedded in the clay about 15 feet from the surface. The boulder had not been moved

PLATE XX.



THE 100 FOOT RAISED BEACH AT KESSOCK FERRY, INVERNESS, SCOTLAND.

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland.

To face p. 367.

out of its original position, and there were remains of Balani on various parts of its surface. With the assistance of the workmen he dug round it, and heaved it out of its bed. He found that the whole underside of it was covered with a close, thick crust of entire Balani, the points of which were sticking downwards into the soft clay beneath, showing clearly that they must have grown upon the stone before it was dropped into its muddy bed. It would be difficult to obtain clearer evidence than this of the action of coast ice, which, forming round about the Balanus-covered boulders of the shore, eventually floated them away, and dropped them in deeper water. Jamieson found some crushed shells of young mussels beneath one of the boulders.

It would be difficult to obtain evidence which would give a more vivid impression of the conditions of the period than that conjured up by the above. The estuary of the Clyde was at that time much more extensive than at present. On its muddy bottom there flourished an arctic fauna. Ice-floes, and perhaps also small icebergs, were studded over its surface, drawing in and out with the set of the tide. Every winter the ice-foot formed along the shores and broke up on the advent of summer, carrying with it its burden of boulders to be distributed far and wide over the bottom of the sea.

Shore-lines of the 100-foot sea.

The shore-lines of this late glacial sea have been traced far and wide throughout Scotland. Locally and irregularly developed from the first, they are now also much denuded and in places extremely difficult to follow. They are best developed in the Western Islands, where, under the influence of the Atlantic waves, immense shingle beaches have been built up.[1] In some parts of the west of Scotland a well-marked rock notch has even been cut at the 100-foot level, as for example near Applecross and on the island of Rum. In general, however, the terrace is one of deposition, and bears witness to the enormous amount of loose material available for re-sorting by the waves at this period. The gravel beaches at the 100-foot level in Islay and Jura, which cover many square miles of ground, are especially striking in this respect, and entirely dwarf the more modern "25-foot" beach, which is in general the best marked shore-line in Scotland. The apparent outer limit of distribution of the 100-foot beach, as traced by the Geological Survey, is indicated in Fig. 127. Several points regarding its distribution are worthy of note. The most remarkable is, perhaps, that on which so much emphasis is laid by Professor Jas. Geikie,[1] namely, the absence of the beach in the upper reaches of the Highland lochs. This is, without doubt, due to the occupa-

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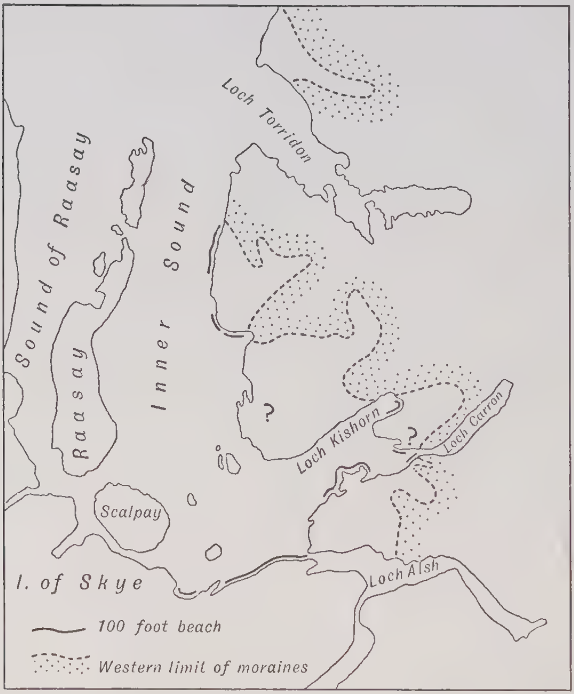
[1] "The Geology of Jura and Knapdale," *Mem. Geol. Survey of Scotland.*

Absence of the 100-foot beach in the upper reaches of the Highland lochs.



Emery Walker sc.

Fig. 127.—Map of the Inner Sound between Skye and the mainland of Scotland, showing the relation of the 100-foot beach to the western limit of the moraine glaciation. (Scale 10 miles to an inch.)

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[1] *The Great Ice Age*, 3rd ed., 1894, p. 276.

tion of these fjords by ice either at the time of or later than its formation. No other agency will explain the abrupt cessation of this feature on reaching a certain point in the fjords. A noteworthy case is that of the Inner Sound between Skye and the mainland. Here on the open coasts the 100-foot beach is well developed, being especially remarkable between Kyleakin and Broadford, and at intervals along the coast north of Kyle of Lochalsh as far as Plocton. East of Plocton there is no trace of a terrace until Strome Ferry is reached. Here, at the narrows which form the mouth of Loch Carron, there are immense gravel embankments which have been regarded by former investigators as deposited in the 100-foot sea. These, we shall shortly give reason to believe, are not beaches at all; but it is at any rate obvious that inside the narrows, and for the whole of the six miles of Loch Carron above Strome Ferry, there is no trace of the 100-foot beach. This upper reach of the loch must have been occupied by ice during or after the formation of the beach, for no other reason can be assigned for its absence, the later beaches at elevations of 50 feet and 25 feet being, according to Dr. Horne, prominently developed at the head of the loch.

Similar phenomena are met with in Loch Kishorn, and have been described by Dr. Horne in a brief note quoted by Professor Geikie. Here the 100-foot beach is met with at the village of Kishorn and at Auchentraid. Not a trace of the beach in question, however, appears on the north side of this sea-loch, where the valley glaciers coming from the lofty mountains of Applecross have left abundant morainic debris below that level.

Along the western sea-board of the peninsula of Applecross the 100-foot beach can be traced northwards from the village of Applecross, either as a gravel terrace or as a ledge carved out of the solid rocks, as far as Chuaig. There it disappears, and it is highly probable that in this case also its abrupt termination may be due to the existence in Loch Torridon of a great valley-glacier during or after the 100-foot depression.[1] In this district, therefore, it is perfectly clear that the "moraine-glaciation" of the Scottish Highlands (see p. 82) excludes the 100-foot beach, and the conclusion is confirmed by similar phenomena in other parts of the country. Whether the maximum extent of the glaciers was contemporaneous with or later than the beach is as yet not perfectly clear, but, in addition to the negative evidence of the absence of the beach inside the glaciated area, there is certain positive evidence tending to show that the sea had already fallen to a low level before the final retreat of the glaciers set in. The gravel embankments at Strome Ferry, referred to above, form part of this evidence. These embankments are not portions of a terrace, but of a steeply sloping fan, the outwash apron of the Loch Carron Glacier, the surface of which has an altitude of 130 feet at the entrance to the narrows, but descends as low as 60 feet in its distal portions. A delta fan laid down in the 100-foot sea might have such a sloping surface, but the slope could hardly extend to a depth of 30 feet or so below low-water mark. It would seem, therefore, as if the continuation of the fan down to the 60-foot level was an indication that the sea had sunk somewhat before the withdrawal of the glacier.

Maximum of the Highland glaciation later than the 100-foot beach: Strome Ferry.

Similar but even more striking examples of this phenomenon are found in the island of Mull, on parts of the coast of which the 100-foot beach is well developed. The beach, however, does not run up into the mountain glens which, for long distances above their mouths, are quite low enough to receive it. The bottoms of these glens are strewn with the moraines of the local glaciers, which extended on all sides from the central mountains after the retreat of the general ice-sheet. In certain cases there is a peculiar gravel formation occupying the lower reaches of the glens. In Glen Forsa this formation is very marked, and consists of small eskers and gravel fans ranged round the lower end of a great central depression, which marks the site of the

Mull.

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[1] *Op. cit.* p. 277.

end of the glacier at the stage when it formed the gravels. The latter are thus clearly outwash gravels, and in one case a small esker is seen to pass at its distal end into a beautifully sloping fan, of which it, so to speak, was the feeder. Now these fans, from the apex to the outer margin, are beneath the 100-foot level, and can be traced seaward down to a height of about 30 feet above the sea, where they are overlain by the gravels of the 25-foot beach. From the slope of their surface they are obviously subaerial outwash fans and not deltas, and their low level excludes any possibility that the sea could have been a hundred feet higher than at present during their formation. Exactly similar gravels occur at the lower end of Loch Ba. Yet the 100-foot beach is well developed in Loch na Keal opposite the mouth of Loch Ba. It does not, however, penetrate into the area of the Loch Ba glacier, and the nature of the outwash gravel shows, just as in Glen Forsa, that the sea had abandoned the 100-foot level before the final retreat of the glacier.

Corran Ferry.

A quite similar case has been discovered by Maufe near Onich in northern Argyll. The great bank of gravels which forms a partial barrier across Loch Linnhe at Corran Ferry is not, as was formerly supposed, a raised beach-spit, but merely a remnant of the outwash gravel of a glacier. It is full of kettle holes and small lakes formed by the enclosing of masses of ice during its formation. The surface of this mass of gravel is about 50 feet above high-water mark, and it clearly could not have been formed while the sea stood at the 100-foot level. This portion of Loch Linnhe is quite free from any remnants of the 100-foot beach, which, however, occurs farther south in the Firth of Lorne.

It might at first sight appear to be a legitimate conclusion from these facts that the local glaciation of the Highlands of Scotland was later than the 100-foot sea, of which it destroyed all traces in the areas invaded by the glaciers. It is necessary, however, in this connexion to remember that the marine clays deposited in this sea contain a highly Arctic fauna, and show unmistakable evidence of the presence of floating ice during their deposition. Whether the glaciers, which must have existed at this stage, were those of which we find a record in the moraines and outwash fans of the Highland glens, or belonged to some earlier and distinct period, it is impossible at present to decide. The only definite conclusion which can be safely drawn from the available evidence is that the sea had fallen from the 100-foot shore-line to near or below the present level before the final retreat of the local glaciers.

The absence of the beach in other districts more difficult to explain.

We thus obtain an explanation of some of the anomalies in the distribution of this remarkable shore-line. There are others, however, which still present difficulties. Thus the 100-foot beach is entirely wanting on the shores of Caithness from Reay to Wick, even in localities where it could scarcely have failed to have left its mark. We can hardly assume the presence of ice over this whole district, for there are no lofty hills to supply the glaciers. Neither has the beach decreased gradually in level and passed beneath the sea, for it attains a splendid development at the full altitude of 100 feet at Golspie in Sutherland and on the Cromarty Firth. Still more curious is the apparent absence of this beach in Ireland when we consider that it is present on the coast of Ayr, no very great distance away. Neither has it been detected in any part of England.

The so-called 50-foot beach of Scotland.

In Scotland, at a lower level than the 100-foot beach, is another raised beach, which commonly goes by the name of the "50-foot" beach. It is certainly later than the 100-foot beach, for, besides occurring at a lower level, it appears to penetrate into some of the fjords where the latter is absent. It is not clear, however, whether it merely represents a stage of the retreat of the sea from the 100-foot level or is the record of a distinct readvance. Neither is it obvious that what has been termed the 50-foot beach is everywhere the same shore-line. Nevertheless, it may be taken as a fairly correct statement of the facts that in most parts of Scotland where the

100-foot beach is developed there is a lower beach at about this level, perhaps ranging up to 65 feet or down to 45 feet.

These beaches which occur in Scotland between the 50-foot and 100-foot levels may clearly be regarded as a group of late-glacial age; for it has been shown that they were contemporaneous with the existence of large glaciers and that the deep-water clays associated with them yield remains of arctic animals. The lower beaches probably mark stages of recovery from the maximum of submergence indicated by the 100-foot beach. We cannot, however, as yet be sure of this, and we have still less knowledge of the conditions which followed upon the retreat of the sea from the 50-foot level. We know that eventually great forests covered the country, which was occupied by a temperate fauna and flora. During this forest period the sea-level was considerably lower than at present, and in consequence we find all around our shores at the present day submerged land-surfaces, forests, and peat-beds. These we shall now briefly consider.

Subsequent emergence shown by the submerged forests.

Some cases of submerged forests described.

The greater number of the recorded submerged forests of the British Isles occur on the foreshore between tide-marks. A few have, however, been proved in constructing docks and making other excavations beneath sea-level, and these are in general the most important, as they lie deeper and prove a greater amount of submergence. A noted case is that of the Pentuan stream-tin section in Cornwall. This section, which was proved in mining for tin, is exhibited graphically in Fig. 128.[1]

The Pentuan stream-tin section in Cornwall.

The lowest beds in the section consist of angular debris resting on some water-worn material, and these together form the "tin ground." In the angular debris are rooted stools of trees at a depth of 50 feet below high water; above this comes a varied series of beds with marine shells, trees, and land animals as indicated. Bones of the whale were abundant from 35 to 25 feet,

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[1] R. A. C. Austen, "Superficial Accumulations of the Coasts of the English Channel," *Quart. Journ. Geol. Soc.*, vol. vii. p. 118 (1851).

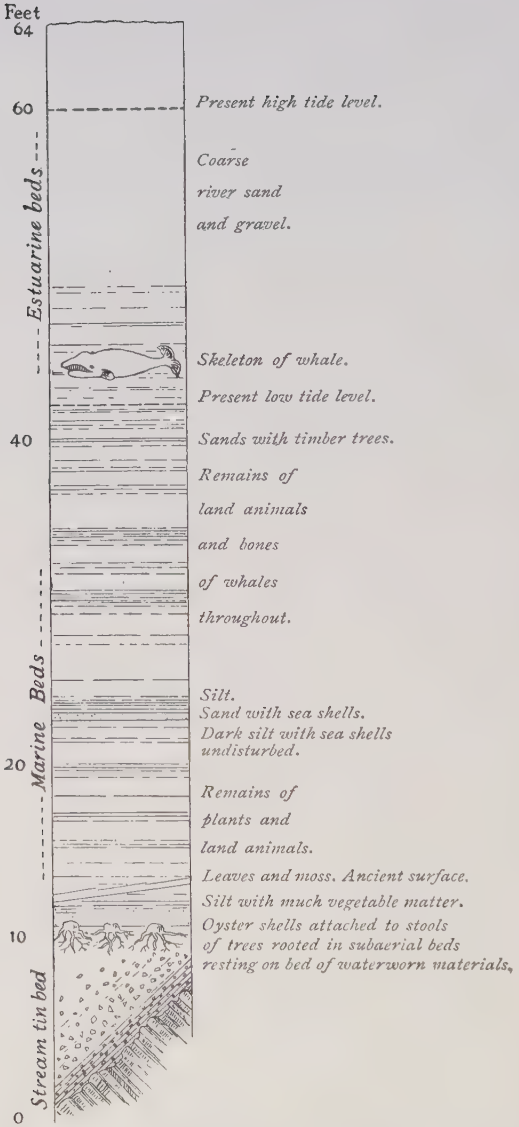

Fig. 128.—Section of the Pentuan Valley Stream-tin Works, Cornwall, showing the submerged forest and overlying marine and estuarine beds. (After R. A. C. Austen.)

and a whole skeleton was found about 15 feet below high-water mark.

The Barry Dock Section, Glamorganshire.

Another famous section is that which was exposed in making the dock at Barry, Glamorganshire, and was examined and described by Mr. Strahan. The following succession of strata was exposed:—

1. Blown sand.
2. Scrobicularia clay.
3. Sand and gravel—base of Scrobicularia clay. Strong line of erosion.
4. Blue silt with many sedges, 1-6 feet.
5. The Upper Peat Bed, 1-2 feet thick, 4 feet below Ordnance datum. This bed yielded a fragment of a polished flint implement.
6. Blue silty clay with many sedges, 5-7 feet.
7. The Second Peat, a thin layer of marsh peat, mostly sedges, 3-8 inches.
8. Blue silty clay same as 6.
9. The Third Peat, many large logs and stools with roots in place 8 inches thick, 20 feet below O.D.
10. Blue silty clay with reeds, willow leaves and fresh-water shells, 12 feet thick.
11. The Fourth Peat, trees and roots in place, land shells, 3-4 inches thick.
12. Old soil, roots and land shells, 35 feet below O.D., resting on rock.

Spring tides rise 20 feet above O.D., and as the trees cannot have grown below high-water mark we may therefore deduce a submergence to the extent of 55 feet since the growth of the lowest forest. In the Upper Peat Bed (No. 5) a broken fragment of a polished axe-head was discovered, together with remains of oak, willow and fir, and the little plant *Naias marina* now confined to Norfolk. The flint was only a fragment, and might possibly have been introduced at any time subsequent to the occupation of the country by Neolithic man. The line of erosion, according to Mr. Strahan, was due to the admission of the sea through a lateral gap.[1]

The Hull Dock Section.

We will give one more example of these submerged forest sections before passing on to more general considerations. It is that which has been exposed in the docks at Hull, and described by Mr. Crofts.[2] The succession of deposits passed through in cutting the dock were, from above downwards:

6. Humber warp (alluvium of the Humber).
5. Shell-bed.
4. Marl.
3. Peat.
2. Red stoneless glacial clay.
1. Gravel and boulder-clay.

High-water of spring tides at Hull is 12 feet above O.D. and low-water 10 feet below O.D. The surface of the peat-bed is 13 feet below O.D. and 25 feet below the level of high-water mark of spring-tides. The bed consists of leaves, bark, wood, and stumps of trees, the latter with roots penetrating in some cases several feet into the glacial beds below. The oak (*Quercus pedunculata*), cherry (*Prunus padus*), birch and hazel were represented.

The peat was covered by a stiff marly clay, filling up all hollows, with its upper surface almost perfectly horizontal and level. In this bed were cherry-stones in considerable quantity, and even many quite perfect cherries. At one spot was a cluster of small pieces of charcoal, but no trace of human agency could be detected.

The shell-bed, which in one part of the section was split into two leaves by a layer of silt, lay immediately on the marl, and over this again came the laminated warp to a thickness of 7 to 12 feet.

The peat-bed of the above section covers the whole of the district round Hull, reaching west as far as Hessle, where it gradually fades away, until at last nothing but a fine line marks the junction of the boulder-clay and warp.

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[1] A. Strahan, "Submerged Land-surfaces at Barry, Glamorganshire," *Quart. Journ. Geol. Soc.*, vol. lii. p. 474 (1896).

[2] W. C. Crofts, "Notes on Sections exhibited during the excavation of the Alexandra Dock Extension, Hull," *Proc. Yorks. Geol. and Poly. Soc.*, N.S. vol. xiv. part ii. p. 245 (1901).

The three sections just described may be taken as typical examples of the submerged forests which abound around the coasts of the British Islands. These prove in the clearest possible manner the occurrence of a post-glacial period of emergence, in which forests flourished throughout the country. The amount of the emergence was at least 55 or 60 feet, and may have been considerably greater. It had a wide range, affecting not only Great Britain and Ireland, but the adjoining coasts of Denmark, Holland, Belgium, and France, and possibly some of the coast of Europe even farther south. In Scandinavia there are no submerged forests, but we can trace here the effects of the general emergence in the abandonment by the sea of both outlets of the Baltic Basin (that across Lake Wener and that of the Sound) and the consequent formation of the Ancylus Lake.[1] In consequence of this extensive range we have come to regard the submerged forest emergence as due to a general lowering of sea-level and not to a deformation of the earth's crust. The latter one might naturally expect to be more localised and to present its effects over a limited area after the manner of the 100-foot beach, which is almost certainly a result of the depression of a restricted area of the earth's crust under a load of ice. We make this theoretical distinction thus early in order to facilitate the understanding of the facts we are now discussing.

Wide distribution of the submerged forests.

Its significance.

In Scotland, the north of England, and the north-east of Ireland, there is present a raised beach, the "25-foot" beach, which is distinctly later than the submerged forest period. This remarkable fact was first noted by Jamieson, and is brought out clearly by him in the famous paper we have cited above. He gives several sections showing the relation of the submerged forest to the

The period of submerged forests separates the period of the 100-foot from that of the 25-foot beach.

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[1] See p. 351.

Sections on the east coast of Scotland.

deposits of this beach and to those of the earlier 100-foot beach. The most striking of these is perhaps that of the estuary of the Ythan in Aberdeen, given in Fig. 129. In this the deposits of the late glacial sea, the 100-foot sea, are shown banked up against a boulder-clay slope. On these glacial marine clays, and passing down beneath sea-level, rests the peat-bed with its trees, and on this in turn the estuarine deposits of the "25-foot" beach.

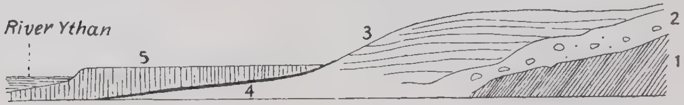

Fig. 129.—Section showing the relations of the superficial deposits in the estuary of the Ythan, Aberdeenshire. (After Jamieson.)

1. Gneiss. 2. Boulder-clay. 3. Late-glacial marine beds. 4. Stratum of peat. 5. Old estuarine beds with shells.

Again, in the valley of the Tay the submerged peat occurs along a stretch of many miles from the mouth of the Earn to Balmerino in Fife. In many places it forms the bed of the estuary, and the roots of it impede the drawing of nets. On the shores it passes underneath the estuarine clay of the 25-foot beach, none of which is ever found below it. The section near Abernethy, given in Fig. 130, shows the relations frequently observable along the shores of the estuary.

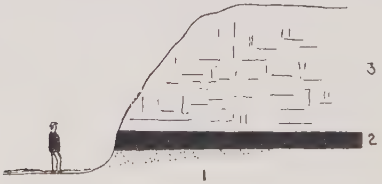

Fig. 130.—Section near Abernethy in Fife, showing the carse clays of the 25-foot beach period overlying a bed of peat. (After Jamieson.)

1. Sand and gravel. 2. Peat full of remains of birch and alder. 3. Carse clay.

At Blair Drummond, in the Forth, is the section shown in Fig. 131, in which the peat-bed is again seen beneath the estuarine clays of the raised beach. In the latter were found the bones of a whale, and on its surface a second peat-bed with roots of oak.

To quote still one more case from the east coast of Scotland. At Montrose, as was proved by Mr. Howden in 1868, there is a peat-bed some distance below sea-level resting on the glacial marine clays of the 100-foot period, and overlain in turn by the later estuarine deposits of the 25-foot.

These sections show beyond a doubt that in the east of Scotland, between the formation of the 100-foot and 25-foot deposits there was a period of low sea-level, and that the 25-foot beach is therefore the result of a quite distinct and much later submergence. We have evidence of a similar succession on the west coast of Scotland and in Ireland, in the occurrence of beds of peat beneath the gravels of the 25-foot beach. The section which, however, shows most clearly of all the relation of this latter beach to the submerged forest period is that exposed in the excavation of the Alexandra Dock, Belfast, and described by Mr Praeger.

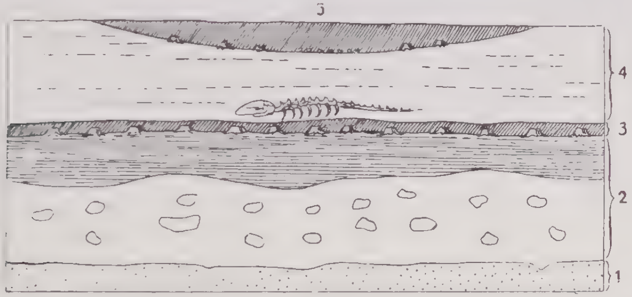

FIG. 131.—Diagram showing the relations of the superficial deposits at Blair Drummond in the Valley of the Forth. (After Jamieson.)

1. Sandstone. 2. Glacial beds. 3. Peat with remains of trees. 4. Carse clay with bones of the whale. 5. Peat with roots of oak-trees at the bottom and remains of an old wooden road.

Evidence of a similar succession on the west of Scotland and in Ireland.

The Belfast Dock section described in detail.

The deposits of the actual raised beach were not exposed in these dock sections at Belfast, but only the estuarine clays formed during the raised beach period. The raised beach itself, however, is splendidly developed at Larne, 18 miles N.N.E. of Belfast. By combining the information obtainable at Larne with that revealed by the Belfast sections a tolerably complete history of the post-glacial changes of level is obtained.

At the base of the Alexandra Dock section, resting immediately on the glacial deposits, is a bed of peat representing an old land-surface, formed at a time when the country stood at least 30 feet higher than at present. In the peat remains of the Irish deer, red-deer, and wild boar occur. Over this bed there is first some sand, then 6 feet of marine clay with a shallow water fauna, and above that 6 feet of clay of a deeper water type, to which local workers on faunistic evidence have assigned a depth of at least 5 fathoms. A submergence of 18 feet[1] below present level, such as would account for the formation of the Larne gravel spit, would provide a depth of very nearly 5 fathoms of water over the surface of the Upper Estuarine Clay.

Overlying the Upper Estuarine Clay is a bed of clean yellow sand full of washed single valves of shells derived in part from the upper clay. This points to a period when the surface of the deep-water clay was raised to near tide level, allowing the waves to wash over it, and eventually to throw down on it a beach deposit. Finally, a slight movement of submergence may be inferred from the fact that this clean yellow beach has been in its turn overlaid by muds full of littoral burrowing molluscs.

The conclusions to be drawn from it

From these data it is clear that we are justified in drawing the following conclusions :

(1) At the period of the formation of the peat-bed the land stood, relatively to sea-level, at least 30 feet higher than at present.

(2) Depression[2] then set in, resulting in the submergence

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[1] This estimate of the amount of submergence is my own. Mr. Praeger considers that a depression of 26 feet below present mean sea-level would be necessary for the formation of the Larne beach-gravels.

[2] The reader will bear in mind that all depressions and elevations of the land mentioned in this summary are *relative to sea-level*, and the sea-level may have been itself undergoing change.

of the peat-bed and the formation of the shallow water estuarine clay. This depression continued comparatively slowly until the land reached a position some 15 feet above its present level.

(3) The depression then became more rapid, and continued until the land stood about 18 feet below its present level. At this stage the upper or deep-water estuarine clay was laid down, and the raised beaches of the surrounding districts and of Larne were formed.

(4) The land then rose until it reached a position some 5 feet above the present, after which it once more sank until it attained its present level.

Mr. Praeger has drawn curves to exhibit graphically the relative motion of land and sea. In constructing such a curve it is necessary either to regard the land as fixed and the sea as altering its level, or the sea-level as fixed and the land as alternately raised and depressed. The sections afford us no means of deciding which actually took place. It is just as likely as not that both land and sea-level changed, but as we are only concerned with their relative motion one of the curves is as good as the other. Mr. Praeger in his paper has constructed both curves, and having already summed up in terms of the motion of the land, we reproduce here that which regards the land as fixed and exhibits graphically the motion of the sea.

In this diagram (Fig. 132) are plotted off on the vertical scale heights in feet above the peat-bed, and on the horizontal scale distances proportional to the thickness of the deposits, the latter being the only indication we have of the lapse of time occupied in their deposition. The sections into which the diagram is divided by the vertical dotted lines represent, therefore, the periods of time during which the peat, grey sand, lower estuarine clay, etc. were deposited. It must, however, be distinctly remembered that they give a very poor idea of the relative length of these periods. The vertical distance of any point on the curve above the horizontal line representing the peat-bed indicates the height of the water surface above the peat-bed at that period, exhibited in a diagram.

and a vertical line drawn through any point on the curve passes (in the wedge-shaped section at the bottom) through all the deposits that had been formed at that period.

The importance of the 25-foot beach.

The reader will now have some idea of the relation of the submerged forest period to that of the so-called "25-foot beach," and we will pass on to a description and discussion of the latter. This beach is by far the most clearly marked post-glacial shore-line in Scotland. Its rock-notches, terraces, and storm beaches are everywhere well preserved and easily identifiable throughout the area of its distribution. It represents a considerably greater amount of erosion and deposition than is apparent on the modern shore, and it is therefore fairly certain that its formation occupied a longer period than has elapsed since it was raised to its present position.

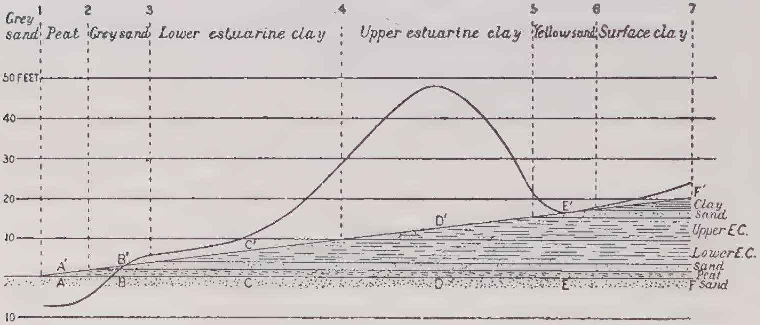
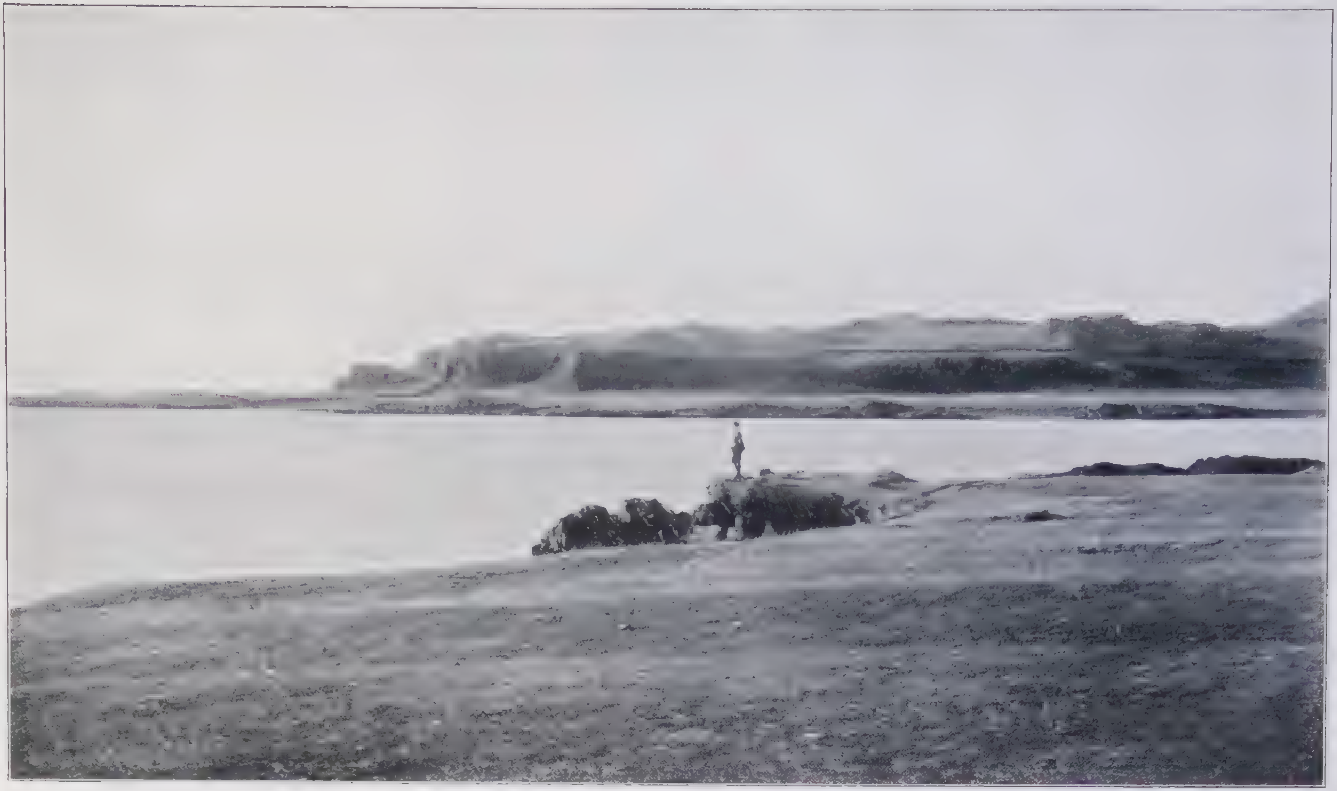


FIG. 132.—Graphic representation of the changes of sea-level in Belfast since the formation of the submarine peat-bed. (After Coffey and Praeger.)

Its elevation, distribution,

The name "25-foot beach," which has hitherto been used to denote the shore-line, is not a very happy one, as it occurs at all heights from sea-level up to 35 feet above the present shore. The term was first applied to the beach in those districts where its inner edge coincides approximately with the 25-foot contour of the Ordnance maps. In the light of our knowledge of its variations in level the retention of the name is hardly justifiable, but it is difficult without anticipating to suggest a better, so we must continue to employ it for the present.



THE SO-CALLED 25 FOOT RAISED BEACH IN LUING, ON THE WEST COAST OF SCOTLAND.

From a photograph by R. Lunn in the collection of the Geological Survey of Scotland.

To face p. 382.

The 25-foot beach is found throughout an oval area embracing the greater part of Scotland, North-eastern Ireland, and the north of England. The area is that embraced within one of the curves in Fig. 151. This curve is the zero isobase along which the beach is actually at sea-level, but it rises steadily towards a centre near Loch Linnhe, where it attains a height of over 35 feet.

and fauna.

The shells found in the 25-foot beach and its associated estuarine clays all occur on our coasts at the present day. The fauna gives no indication of arctic conditions such as we find in the clays of the 100-foot beach. All the differences that can be detected are certain minor changes in the distribution of species, of so slight a character that without supporting evidence no certain conclusion could be drawn from them concerning the climatic conditions of the periods of their formation.

The associated estuarine deposits.

The estuarine deposits of the 25-foot beach present some features of considerable interest. They attain a remarkable development at the head of the Firth of Tay and the Firth of Forth, where they form the level carse lands so famous for their fertility. In the lower reaches of the Tay Valley the carse clays contain estuarine shells such as *Scrobicularia piperita*, but higher up they yield as a rule no shells of any kind, and pass gradually into river deposits. Underneath the clays is the above-described submerged peat and forest bed, which gradually rises as it is traced up the river, so that at Perth and at Easter Balgour, in the valley of the Earn, it reaches 6 to 9 feet above high water.[1] In the Forth similar relations obtain, the carse clays yielding marine shells in the stretches near the sea and passing into river deposits higher up. Skeletons of the whale have been found in several places embedded in the clays. Several dug-out canoes have also been found, and one of these at Friarton, Perth, rested on the peat-bed beneath the whole thickness of the carse deposits.[2]

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[1] Jas. Geikie, *The Great Ice Age*, 3rd ed. pp. 291, 295 (1894).

[2] *Ibid.* p. 291.

Neolithic age of the 25-foot beach.

It is a remarkable fact, that just as in Denmark and Scandinavia the earliest traces of Neolithic man are associated with the highest shore-lines of the Littorina-Tapes depression, so in the British Isles they occur in the gravels of the 25-foot beach. This was first established by Du Noyer[1] in the north of Ireland in the year 1869. He pointed out, moreover, that these implements were of a rather rude type, and contrasted them with the more perfect forms found on the surface in various localities, the latter including beautifully-shaped arrow or javelin heads with barbs. He concluded that the men who made the first-mentioned ruder implements lived during the formation of the raised beach, while the more perfect types he regarded as being indicative of much greater skill and as being later in age.

Doubt having been cast on Du Noyer's statement that the implements were actually contained in the gravel of the raised beach, a committee of the Belfast Naturalists' Field Club was appointed in the year 1886 to make excavations in the famous raised gravel-spit in Larne Harbour, County Antrim, with the object of putting this point to the test. The final report of this committee, drawn up by R. Ll. Praeger[2] in 1889, proved that *near the landward end of the spit* the gravel contained implements to a depth of 19 feet from its surface, that is, throughout almost its entire thickness, a fine example of a rude axe-head being found at a depth of 11 feet from the surface.

Its elevation almost completed in Neolithic times.

More recently Messrs. Coffey and Praeger[3] have carried out a more extended series of investigations into the Neolithic deposits of the north of Ireland, and have succeeded in establishing the important fact, that the elevation of the land which brought the beach into

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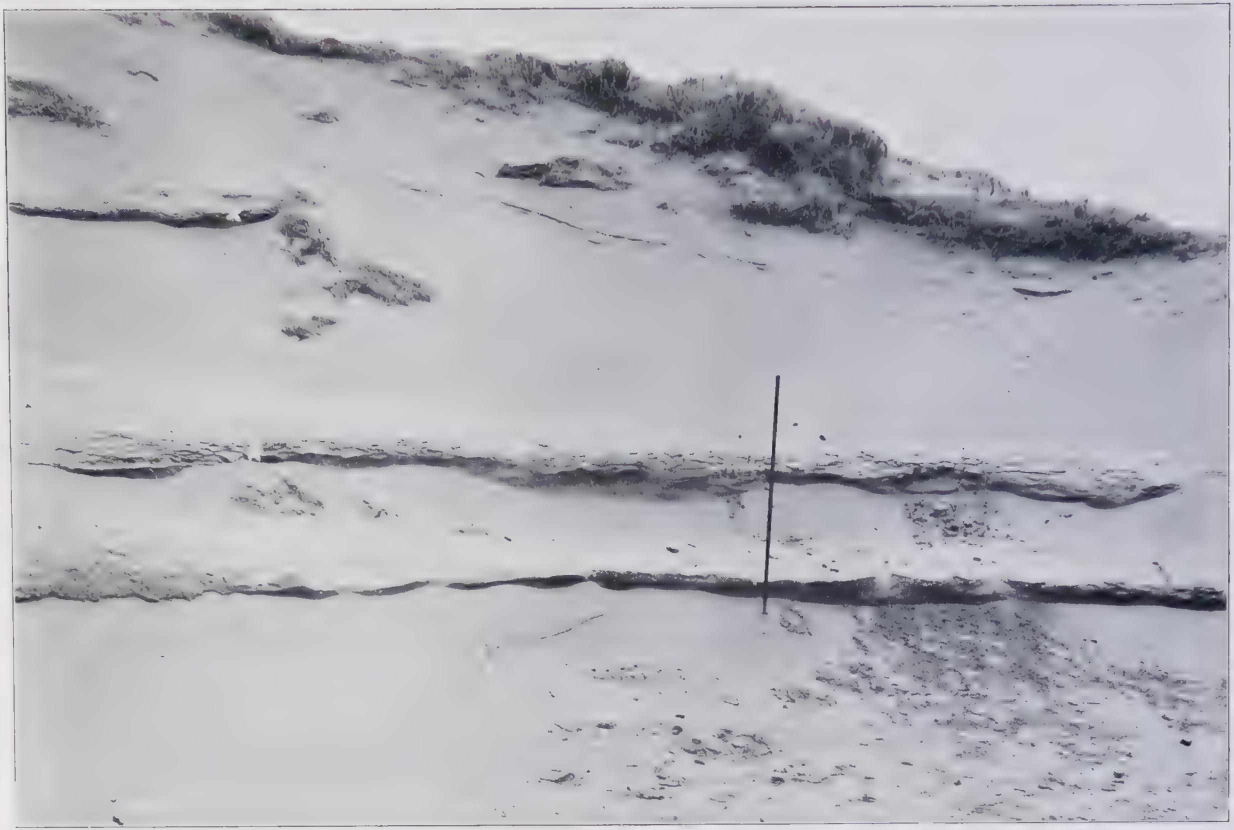
[1] G. V. Du Noyer, "On Flint Flakes from Carrickfergus and Larne," *Quart. Journ. Geol. Soc.*, vol. xxv. p. 48 (1869).

[2] *Proc. Belfast Nat. Field Club* (2), iii. pp. 189-210 (1890).

[3] George Coffey and R. Lloyd Praeger, "The Larne Raised Beach, a Contribution to the Neolithic History of the North of Ireland," *Proc. Roy. Irish Acad.*, vol. xxv. sec. C. p. 146 (1904).

PLATE XXII.



NEOLITHIC LAYERS IN THE SANDHILLS OVERLYING THE GRAVELS OF THE RAISED BEACH AT PORTSTEWART, CO. LONDONDERRY, IRELAND.

From a photograph by R. Welch.

To face p. 384.

its present position was almost entirely if not quite completed during Neolithic times. This has been effected by a determination of the levels of the Neolithic floors in the sand dunes which overlie the raised beach gravels of Whitepark Bay on the north coast of Antrim and Portstewart in Londonderry. It has also been proved by them, in confirmation of Du Noyer's idea of an earlier and later stage of culture, that the industry at these sites is quite distinct in character and of a more advanced type. The nature of the flaking is somewhat different, and polished axe-heads have been found in all the localities examined.

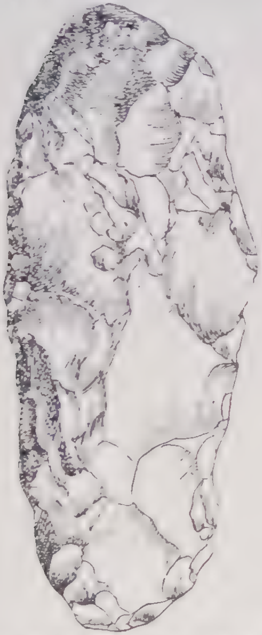


FIG. 133.—The Larne type of axe-head. (After Coffey and Praeger.)

Identity of the Larne and Nöstvet types of axe-head.

It is very remarkable that the rough-hewn axe-heads of the Larne raised beach gravels, called by Messrs. Coffey and Praeger the "Larne type," are identical, if we neglect the difference of material which is determined by local circumstances, with the axe-heads of Nöstvet type which Professor Brögger finds to be associated with the highest shore-line of the Littorina-Tapes depression (see Chap. XV.). We must remember, however, as Messrs. Coffey and Praeger point out, the Larne spit was not a dwelling-place, but only a workshop, where the axe-heads may possibly have been merely roughed out, and taken away to be finished elsewhere.

Relation of Neolithic remains to the 25 foot beach in the Isle of Man.

In the Isle of Man Mr. Lamplugh found that the worked flints were plentiful on the surface of the inner portions of the wide gravel platform of the raised beach, which has there an altitude of 10 or 12 feet above high-water mark, while they were absent except as rolled fragments on the seaward portions. He concluded that "at any rate part of the platform was in existence in Neolithic times, but that it may not have attained its full breadth until after the close of that period."[1]

and in Scotland.

Coming now to Scotland, we find several cases somewhat like that described by Mr. Lamplugh. In the famous sands of Luce the Neolithic remains occur in the landward part of the sand-hills overlying the gravels of the raised beach, whilst in the seaward part of the dunes they are quite absent.

Similarly at Balnahard, in the north end of Colonsay, the sand-hills contain a Neolithic floor, which lies at a height of 22 feet above high-water mark, and never descends below this level, the seaward portion of the dunes showing no trace of it. The elevation of the "25-foot" beach here is from 22 to 24 feet.[2]

Where the river Avon enters the carse lands of the Forth there are a number of kitchen-middens or prehistoric refuse heaps, described by Dr. Peach, all of which occur either on the bluff which borders the carse, or just at its base, "as if, when it was the limit of high water, the people who formed the middens, after searching the shores during low water, had retreated thither to enjoy their feast while the tide covered their hunting ground."[3]

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[1] G. W. Lamplugh, "The Geology of the Isle of Man," *Mem. Geol. Survey.*

[2] W. B. Wright and Angus M. Peach, "The Neolithic Remains of Colonsay," *Geological Magazine*, vol. viii. p. 164 (Dec. 5, 1911).

[3] *Mem. Geol. Surv. Scotland.* Explanation of Sheet 31, p. 54. Edin., 1879.

CHAPTER XVII

THE LATE GLACIAL CHANGES OF LEVEL IN NORTH AMERICA

The Champlain Epoch—Its late-glacial age—The ice-dammed lakes of the Great Lakes region—Tilting of their shore-lines—The Erie-Ontario basin—Lakes Maumee, Whittlesey, Warren, and Iroquois—Northern limit of horizontality of the shore-lines of Lakes Maumee and Whittlesey—The Michigan-Superior-Huron basin—Lake Chicago—Northern limit of horizontality—The Algonquin shore-line—Lake Nipissing—The Onekama hinge-line—The effect of outlets on the northward splitting and tilting of the shore-lines—Lake Agassiz—Gilbert's measurement of the recent tilting in the Great Lakes.

In the two preceding chapters some account has been given of the remarkable oscillations of level which affected Scandinavia, the British Isles, and the north-west of Europe generally during late-glacial and post-glacial times. Canada and the United States underwent similar changes, the records of which are preserved to us in the elevated marine sediments along the coast, and the ancient warped and tilted shore-lines around the Great Lakes. Unfortunately, in the study of their post-glacial marine sediments the Americans are far behind, but they have carried out a series of researches on the shore-lines around their lakes, which rival in interest the magnificent results attained by the Scandinavians.

The Champlain marine deposits.

From New York northwards along the American coast there are preserved here and there very extensive deposits of marine clay and old sea beaches at considerable heights above present tide level. These remnants of submergence vary greatly in altitude, but the upper limit rises, as far as is known, fairly steadily towards the north. The period of formation of these deposits is generally known as the Champlain Epoch, from Lake Champlain, around which they are typically developed. An arm of the sea at this stage extended up the St. Lawrence Valley to Lake Ontario. It filled the basin of Lake Champlain, and probably connected southward with the sea at New York by a narrow strait extending along the Hudson Valley. Marine shells and bones of the whale and other marine animals have been obtained from these deposits. They are found around Lake Champlain at altitudes varying from 400 feet or less about the south end of the lake to 500 feet at the north end, and also at an altitude of 600 feet near the east end of Lake Ontario. Deposits of this stage are known in Connecticut, but they have been best studied in Maine, where they have a well-defined upper limit of about 230 feet above the sea, and have yielded many marine fossils, including species of Mya, Astarte, Leda, and Yoldia. G. H. Stone has given an excellent account of the Maine deposits, and demonstrated very clearly their intimate connexion with the glaciation. He points out that the kames and eskers on coming down to the 230-foot level spread out into great gravel deltas, the material of which is found to become finer and finer at greater distances from the old shore-line, passing first into sand and ultimately into marine clay. There appears to be little doubt that the sea stood at the 230-foot level while the ice-sheet still covered the State of Maine, and that the subglacial streams in many cases discharged directly into the sea.[1]

Even less is known about the Champlain deposits of Canada than about those of the United States. Bell[2] has described post-glacial deposits with marine fossils which occur up to elevations of about 600 feet above

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[1] G. H. Stone, "Classification of the Glacial Sediments of Maine," *American Journal of Science*, 3rd Ser. vol. xl. p. 122 (1890); and "The Glacial Gravels of Maine," *Monograph xxxiv.* U.S. Geol. Survey (1899).

[2] R. Bell, "Proofs of the Rising of the Land around Hudson Bay," *American Journal of Science*, 4th Ser. vol. i. p. 219 (1896).

St. James' Bay, and traces of post-glacial submergence are reported at still greater heights in Labrador.[1]

The Great Lakes region.

We will now turn to the much more satisfactory question of the late-glacial and post-glacial warping of the Great Lakes region. The principal contributions towards its solution have been made by Spencer, Gilbert, Warren Upham, Leverett, Taylor, and Goldthwait. The main upshot of these studies has been to prove that immediately after the retreat of the ice the whole region was subjected to a slow and probably intermittent differential uplift, which was greatest in the north and died away gradually southwards. This is shown by the study of the tilting of the shore-lines of the glacially dammed lakes. As the ice withdrew northward, a series of immense lakes were held up between its margin and the high ground to the south, draining over the lowest passes. On the further retreat of the ice-margin these coalesced with one another, and lower outlets becoming available the surface of the water was reduced at intervals to lower levels. A whole series of shore-lines was thus produced, each of which shows a different degree of tilting, the oldest invariably rising quickest when traced northwards. This uplift, which was going on more or less continuously during the whole complex history of the lakes, has the appearance, however, of having had a somewhat intermittent character, for individual shore-lines corresponding to a definite outlet are often found when traced northward to split up into two, three, four, or more subsidiary shore-lines, all distinct from one another, and evidently corresponding to pauses in the uplift. In order to give a better conception of the evidence on which this splendid generalisation is based, and to bring out certain refinements which recent researches have made possible, an attempt will now be made to trace in detail the history of

Tilted shore-lines of the ice-dammed lakes.

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[1] For general account of Champlain deposits, and further references, see Chamberlin and Salisbury, *Geology*, vol. iii. p. 399 (1906). See also Gerard De Geer, "On Pleistocene Changes of Level in Eastern North America," *Proc. Boston Soc. Nat. Hist.* vol. xxv. p. 454 (1892); and Warren Upham, "The Glacial Lake Agassiz," p. 504, *Mon. xxv.* U.S.G.S. (1895).

the different basins in which the successive lakes were formed.

The Erie-Ontario Basin

The earliest of the glacial lakes held up in the Erie

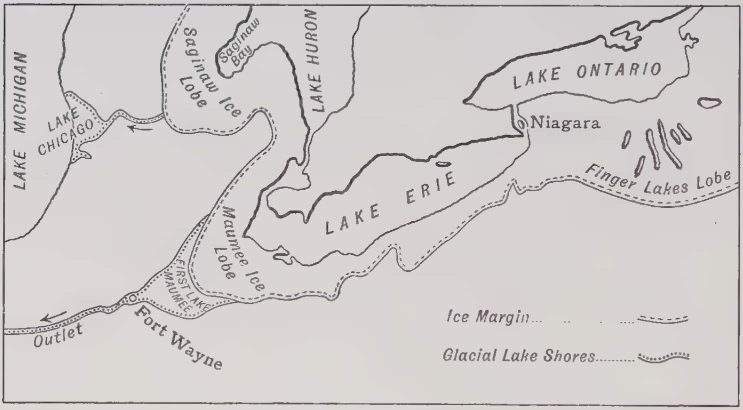


FIG. 134.—Map of First Lake Maumee and contemporary glaciation. (After Leverett and Taylor.)

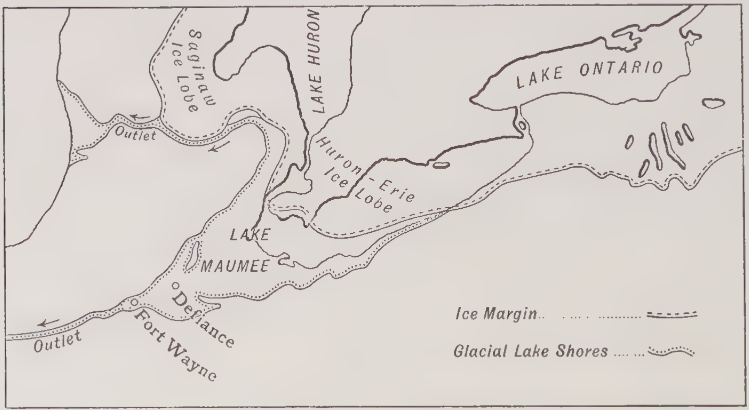


FIG. 135.—Map of Lake Maumee at its greatest extent when it possessed two outlets. (After Leverett and Taylor.)

Lake Maumee.

Basin was Lake Maumee. Two stages have been distinguished to which various names have been given, but which are best known, following Leverett, as First Lake Maumee and Second Lake Maumee. The conditions during these two stages are shown in Figs. 134 and 135. During the first stage the ice-margin stood at the Defiance moraine, and the outlet was to the west by Fort Wayne into the Wabash River, and thence to the Mississippi. This outlet was in use throughout the whole history of the lake, which, however, in its later stages appears to have had two outlets, the second being *via* Imlay into the basin of Lake Michigan.

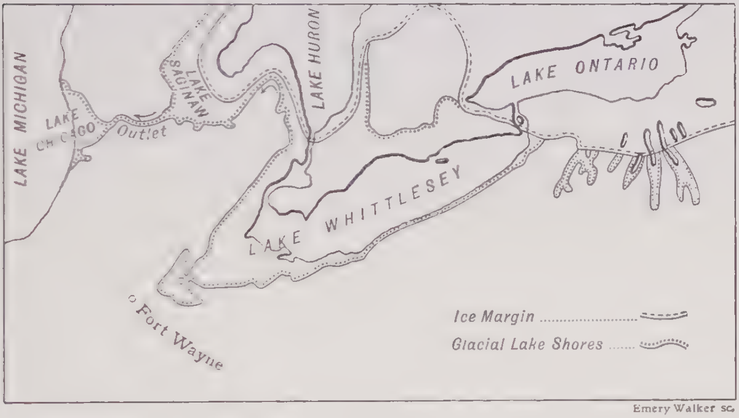


FIG. 136.—Lakes Whittlesey and Saginaw at their greatest extent. (After Leverett and Taylor.)

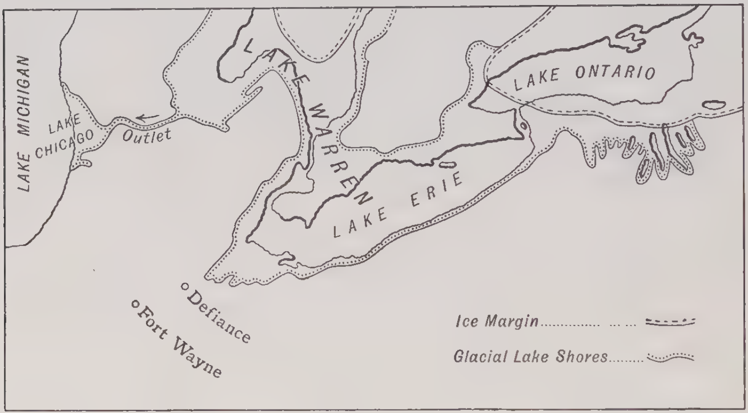
Lake Whittlesey.

This stage of two outlets, however, was probably not of long duration, and further retreat brought about the Lake Whittlesey stage, the conditions during which are exhibited in Fig. 136. The Fort Wayne outlet was now abandoned, and the drainage passed *via* Ubly into Lake Saginaw, now first initiated, and thence by the Grand River into the basin of Lake Michigan. The next stage was that of Lake Warren, the largest body of water formed in this region during the retreat of the ice. It covered the whole area of Lake Erie and portions of Huron and Ontario, extending over the site of Niagara,

Lake Warren.

and connecting up east with the remarkable Finger Lakes of New York.[1] Unfortunately, the limits of Lake Warren in the State of Michigan and in Ontario are as yet imperfectly known, so that only its southern portion can be shown on a map (see Fig. 137). The outlet was the same as that of Lake Saginaw in the Whittlesey stage.

The Lake Warren stage was brought to an end by the opening of outlets to the east in New York. The ponded waters now fell rapidly, forming only a few feeble shore-lines. To one of these stages Fairchild has given the name of Lake Dana, but its beaches have not as yet been traced over any extended area. There was no pause of real importance until the Niagara River came into existence, and Erie became separated from Ontario and began its existence as an ordinary lake. The ice-dammed waters were now confined to the basin of Lake Ontario, where they formed what is known as Lake Iroquois, so named by Spencer because of the use made of the shore-line by the Iroquois Indians as a trail.



Emery Walker sc.

Fig. 137.—Lake Warren at its greatest extent. (After Leverett and Taylor.)

Lake Iroquois.

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[1] Fairchild, "Glacial Waters in the Finger Lakes Region of New York," *Bull. Geol. Soc. Am.* vol. x. p. 27 (1899).

This lake, which is shown in Fig. 138, had its outlet at Rome along the Mohawk Valley.[1] The later stages are not so accurately known, but it would appear that further retreat opened up a still lower outlet along the northern slopes of the Adirondacks into the glacial Lake Champlain, which was held up in the Champlain basin, and drained southward into the Hudson River. Finally the overflow waters were discharged directly into the Champlain arm of the sea.[2]

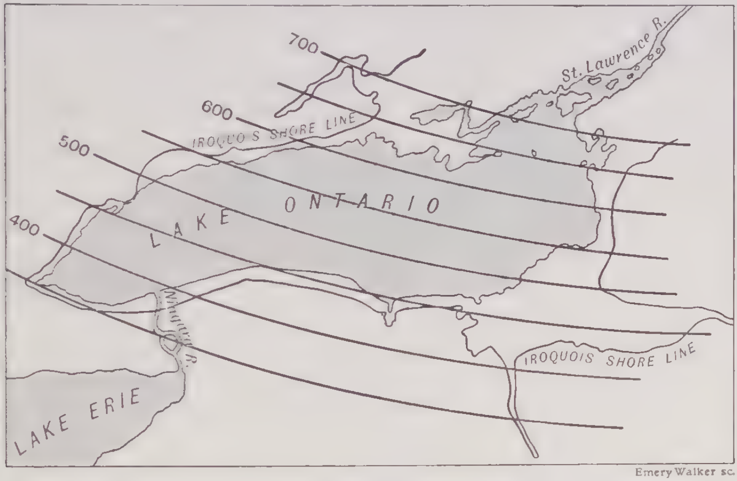

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FIG. 138.—The Iroquois shore-line and the isobases of Lake Iroquois. (After Gilbert.)

Warping of the shore-lines.

Let us now pass in review what is known about the warping of the shore-lines of these various glacial lakes. Here we come at the very outset on a remarkable exception to the rule that the earliest shore-lines are most tilted. *The shore-line of Second Lake Maumee at its south-western end is quite horizontal.* Whether the beach be traced along the north-western or south-eastern shore the result is the same. The calculated position of the old water surface shows for long distances no departure from absolute horizontality, which is not included within the limits of error inseparable from such measurements. On the north-western shore tilting first sets in between Plymouth and Birmingham, and on the south-eastern shore between Cleveland and Ashtabula close to the Ohio-Pennsylvania boundary. This means that to the south-west of the line showing the northern limit of horizontality on the map (Fig. 139) there has been no tilting in post-glacial times. To the north-east of this line, however, the shore-line rises fairly rapidly, the level at Imlay being about 70 feet above that at Birmingham, and that at the termination of the beach in western Pennsylvania about 15 feet above that at Cleveland.

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[1] Leverett, "Glacial Formations of the Erie and Ohio Basins," U.S.G.S. *Monograph xli.* pp. 710-775 (1902).

[2] Chamberlin and Salisbury, *Geology*, vol. iii. p. 399 (1906).

Southern limit of tilting.

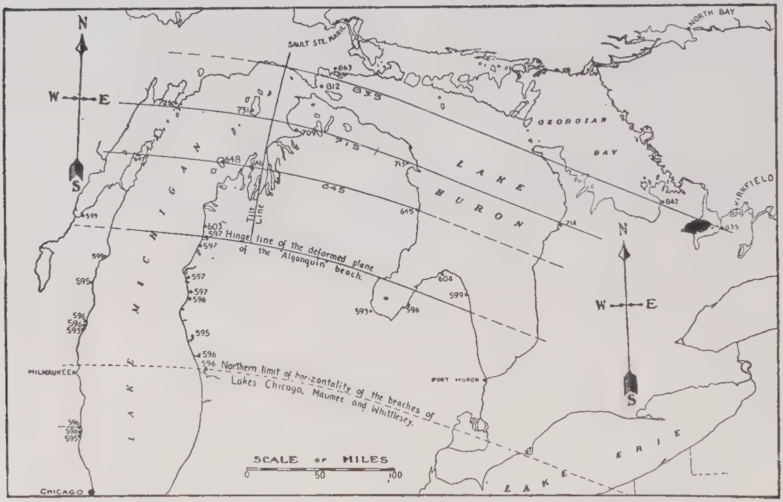

FIG. 139.—Map showing the southern limits of tilting in the Michigan, Huron, and Erie basins. (After Goldthwait.)

The shore-line of Lake Whittlesey shows a similar horizontality for the distance of 200 miles from near Defiance eastward to Ashtabula, but here it begins to rise, and at Murilla in New York is 150 feet above its level at the Ohio-Pennsylvania line. This is an average rise of 1 to 2 feet per mile over a distance of 125 miles.

The shore of Lake Warren, like that of Lake Whittlesey, shows marked differential uplift in passing east from the Ohio-Pennsylvania boundary. At the State line it is only 10 feet higher than at Cleveland, nearly 70 miles to the west, while at Westfield, 55 miles to the east, it is 42 feet above its altitude at the State line. This latter measurement gives a tilt of about 9 inches in the mile.[1] The northward rise of this beach in Michigan is, according to Gilbert, about 1½ feet per mile.

Passing now to the Ontario basin, we find that the Iroquois shore-line is tilted throughout the entire distance over which it has been traced on both sides of the lake. The deformation is indicated approximately by the isobases in Fig. 138, after Gilbert.[2]

The net result of these measurements is that there is a more or less distinct limit to the horizontality of the glacial shore-lines in the Erie basin, that this line is approximately the same for all the shore-lines, and that N.N.E. of this line the shore-lines rise at first very gradually, but afterwards with steeper gradients. The gradients of the older beaches are, moreover, always steeper than those of the younger ones.

The Michigan-Superior-Huron Basin

Lake Chicago.

Of the shore-lines around Lake Michigan certain are confined to the southern part of the basin. These were formed by the glacial Lake Chicago, which had its outlet into the Desplaines Valley at Chicago. Three successive stages have been distinguished by Leverett and Alden, and named by them as follows :

	Height of Shore-line	
	Above Lake.	Above Sea.
Glenwood Stage	55 feet	636 feet
Calumet Stage	38 ,,	619 ,,
Toleston Stage	23 ,,	604 ,,

The history of the formation of these shore-lines is,

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[1] Leverett, "Glacial Formations of the Erie and Ohio Basins," U.S.G.S. *Monograph xli.* pp. 710-775 (1902).

[2] Gilbert, "Earth Movement in the Great Lakes Region," U.S.G.S. *18th Ann. Rep.*, 1897, p. 604.

Horizontality of shore-lines towards the south.

unfortunately, somewhat obscure. They appear to have been determined by the cutting down of the outlet to different levels. There is, however, an indication of a period of low water between the Glenwood and Calumet stages in the occurrence of peaty deposits beneath the Calumet beach.[1] Some doubt also seems to exist as to whether the lake which formed the Toleston beach actually overflowed through the Chicago outlet.[2] These shore-lines, however, all agree in maintaining a perfect horizontality throughout the southern part of the Michigan basin. As in the case of the Maumee and Whittlesey beaches of the Erie basin, there is a fairly distinct northerly limit to this horizontality. North of a line joining Milwaukee and Grand Haven a distinct rise sets in, but it is very hard to trace the beaches much farther. It would seem as if the ice-margin, during the Glenwood and Calumet stages at any rate, was not very far north of this.

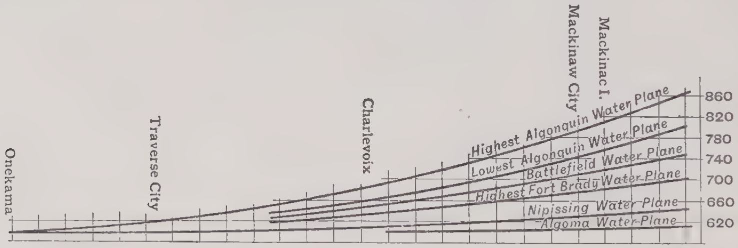

Fig. 140.—Profiles of shore-lines on the east side of Lake Michigan, showing the different rate at which they rise northward. The horizontal divisions mark intervals of five miles The vertical scale is 500 times the horizontal. (After Goldthwait.)

The Algonquin shore-line.

Below the beaches of Lake Chicago, encircling the south end of Lake Michigan, is the Algonquin Beach. It lies about 12 or 15 feet above the surface of the lake. It is horizontal like the Glenwood, Calumet, and Toleston shore-lines, but, strange to say, its horizontality extends farther north, even farther than the beaches of Lake

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[1] Leverett, *The Illinois Glacial Lobe.*

[2] Goldthwait, "A Reconstruction of Water Planes of the Extinct Glacial Lakes in the Lake Michigan Basin," *Journal of Geology*, vol. xvi. p. 459 (1908).

Chicago have been traced. There is no sign of any warping until Onekama is reached, and even then the rise sets in very gradually. At Traverse City it is 1·00 foot per mile, at Beaver Island 2·00 feet per mile, thence north to Mackinac Island 3·30 feet per mile, and between Mackinac Island and Hessel 3·73 feet per mile.

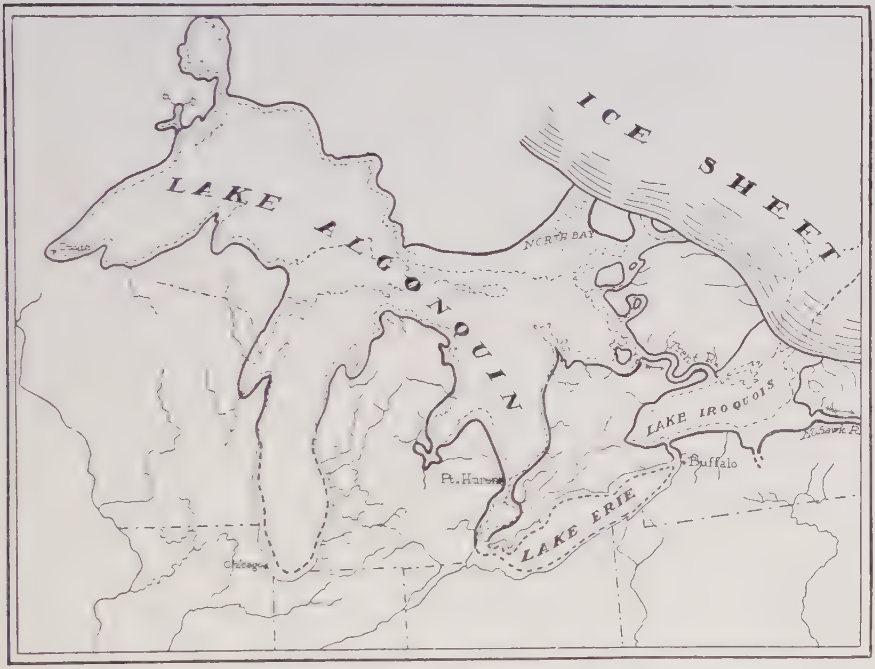

Fig. 141.—Map of Lakes Algonquin and Iroquois. (After Chamberlin and Salisbury.) The theoretical submerged portions of the shore-line in Lakes Michigan and Erie should be disregarded as they are not in conformity with recent investigations.

Splitting of the Algonquin shore-line.

Another interesting peculiarity of this Algonquin shore-line is the manner in which it splits up into subsidiary shore-lines when traced northward. These shore-lines are all warped to different extents, so that while they coincide in the south, they are separated by considerable vertical heights in the north end of the Michigan basin. The relation of these beaches is shown in Fig. 140, which exhibits the profiles of the successive beaches on an exaggerated vertical scale. The uppermost of these is the first or main Algonquin beach, for which the figures have been quoted above. At the stage of the formation of this beach Lake Algonquin, which was sufficiently large to cover the combined basins of Lakes Superior, Michigan, and Huron, had two outlets, one at Port Huron and one east of Kirkfield, Ontario, where there was an overflow into the valley of the Trent River. These two outlets must have come into action almost simultaneously, because, if the Port Huron outlet was operative for any length of time before the Trent outlet was uncovered, there should be a beach in the Huron and Michigan basins above the Algonquin shore-line of the two outlet stages, and no such beach is anywhere to be seen. The necessary condition for the absence of this higher shore-line would be fulfilled if the retreat of the ice-margin from the north end of the peninsula of Michigan to the Trent outlet took place very rapidly.

Outlets of Lake Algonquin.

After a time, however, progressive tilting raised the Trent outlet above the level of the Port Huron outlet, and so put it out of operation. During the succeeding period, when the Port Huron outlet was alone active, progressive tilting went on, apparently in fits and starts, and the Lower Algonquin, Battlefield, and Fort Brady shore-lines were in turn formed.

Lake Nipissing.

Soon, however, a new order of things was introduced by the retreat of the ice-margin to the north of Lake Nipissing, in consequence of which a still lower outlet was exposed *via* North Bay into the Ottawa River. In this manner was inaugurated the Quaternary Great Lake Nipissing, which covered the combined areas of Lakes Superior, Michigan, Huron, and Georgian Bay. Unlike its predecessor Lake Algonquin, however, it was not an ice-dammed lake, and, in a sense, represents the initial stage of the present Great Lakes. Further warping finally transferred the outlet to Port Huron, and so brought about the present state of affairs.

The fact that all the shore-lines below the Algonquin

The Onekama hinge-line.

appear to converge on the line through Onekama, which marks the northern limit of horizontality, is of considerable significance. Goldthwait has called this line the hinge-line, conceiving it to be a line of weakness in the earth's crust about which the tiltings took place. The term is a useful one, but it must not be taken to imply that there is any sudden change from a horizontal to an inclined position. On the contrary, all the available measurements are quite in accordance with the idea that the warping commences very gradually when the line is passed and increases steadily northwards. The isobase through an outlet which lies within the warped area must of necessity be a line of splitting of the shore-lines. The Onekama line, however, passes through no outlet. The northern limit of horizontality of the beaches of Lake Chicago is also a hinge-line both for these beaches and for those of Lakes Maumee, Whittlesey,

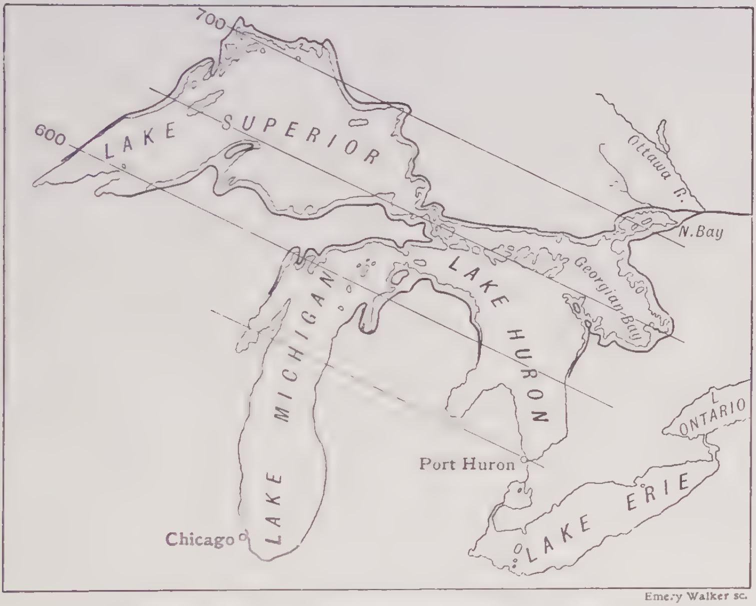

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FIG. 142.—Shore-line and isobases of Lake Nipissing. (After Gilbert.)

and Warren in the Erie basin. It does not pass through any outlet either.

The semi-theoretical diagrams in Fig. 143, after Goldthwait, give a very good conception of the effect of

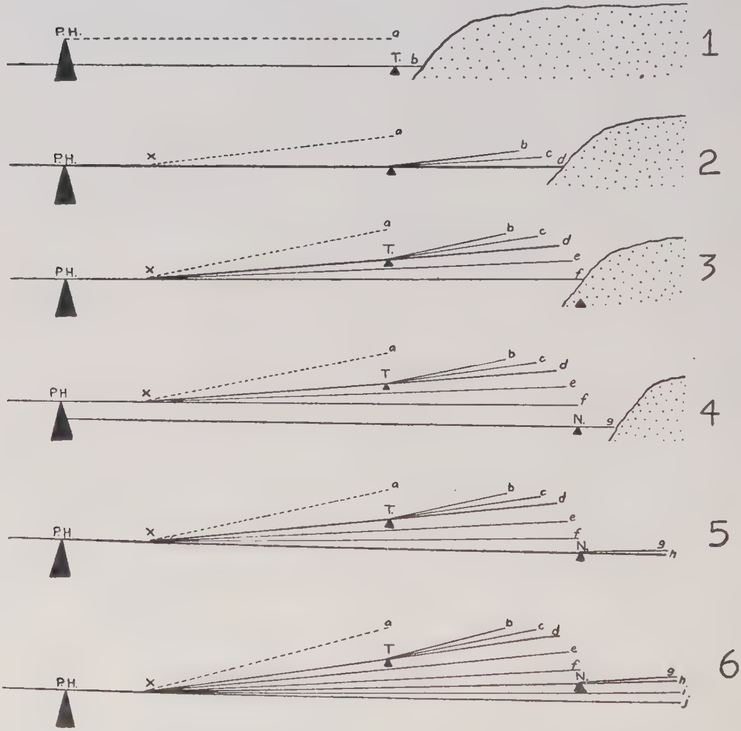

FIG. 143.—Semi-theoretical diagram exhibiting six successive stages in the formation and warping of the shore-lines of Lakes Algonquin and Nipissing.

X. The Onekama hinge-line. P.H. The Port-Huron outlet. T. The Trent outlet. N. The Nipissing outlet. *a*, Early Algonquin beach, unknown in the Michigan basin, but theoretically necessary in the Huron basin; *b*,*c*, planes of temporary low-water stages through the Trent outlet; *d*, plane of the Algonquin beach; *e*, plane of the Battlefield beach; *f*, plane of one of the Fort Brady beaches; *g*, plane of a temporary low-water stage through the Nipissing Pass, possibly marine submergence; *h*, plane of the Nipissing shore-line; *i*, plane of the Algoma shore-line; *j*, present plane of Lake Michigan.

the Onekama hinge-line and the various outlets on the splitting and tilting of the shore-lines formed during the complicated history of the Great Lakes Algonquin and Nipissing. For simplicity it is based on the conception of uniform tilting rather than warping, but the reader will see that this change does not essentially alter the argument. The profile of the Michigan shore-lines given in Fig. 140 lies entirely between the points X and T, representing the Onekama hinge-line and the isobase of the Trent outlet in this series of diagrams. The reader will do well to study this figure carefully in connexion with the foregoing description.

Correlation.

We have considered the Erie-Ontario and Michigan-Huron basins separately because of their more or less independent history. It is, however, quite possible to correlate the various lakes in the different basins with one another. Thus Lakes Maumee, Whittlesey, and Warren were contemporaneous with Lake Chicago. In fact, Lake Maumee during its later stages and Lakes Whittlesey and Warren throughout their entire existence drained into Lake Chicago along the Grand River. At this period there was also another lake, Lake Duluth, held up by the ice in the south-west end of the Superior basin. Its shore-lines do not, however, seem as yet to have been closely studied. Lake Algonquin was contemporaneous with Lake Iroquois, into which it drained, directly along the Trent outlet, and indirectly by Port Huron, Lake Erie, and the Niagara River. The Nipissing stage seems to have been contemporaneous with the greatest extension of the Champlain arm of the sea, which may possibly at this stage have penetrated even into Lake Ontario.

Lake Agassiz.

At a stage in the retreat of the ice-margin, probably corresponding roughly with that of the great lakes just described, an immense ice-dammed lake came into existence in Central Canada in the area now occupied by Lakes Manitoba, Winnipeg, and Winnipegosis. This, the greatest of all the glacial lakes of North America, has been made the subject of an elaborate monograph by Warren Upham,[1] and named by him Lake Agassiz, in honour of the famous pioneer of glacial geology. It had its outlet to the south by way of Lake Traverse,

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[1] Warren Upham, "The Glacial Lake Agassiz," U.S. Geol. Surv. *Monograph xxv.* (1896).

Browns Valley, Big Stone Lake, and the Minnesota Valley to the Mississippi. No less than seventeen shore-lines in the northern part of the lake area were formed contemporaneously with this southern outlet. Owing to progressive warping, similar to that which took place in the region of the Great Lakes during the retreat of the ice, these are separated by considerable vertical intervals, but towards the south they, of course, converge to the level of the outlet. Later the lake was further reduced by the opening of successively lower avenues of discharge towards the north-east. During these stages fourteen more shore-lines were formed.

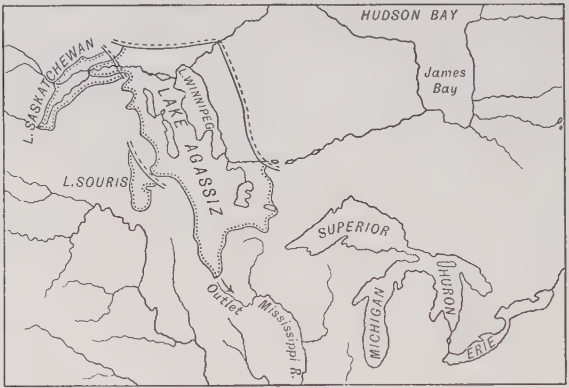

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Fig. 144.—Sketch map showing the position and extent of Lake Agassiz and the earlier glacial Lakes Souris and Saskatchewan. Notation as in Fig. 134. (After Warren Upham.)

Recent warping in the Great Lakes region.

Certain measurements of recent changes of level in the Great Lakes made by Gilbert[1] are of remarkable interest in showing that the warping is still in progress. He was led to make these measurements by observing that the lower reaches of the post-glacial valleys of the streams which enter Lakes Erie and Superior on their southern shores were submerged beneath the waters of the lakes. The permanent submergence of certain low-lying meadows, which had stood within the memory of man well above the water level, seemed to show that this drowning of the southern shores was still going on. Gilbert, accordingly, selected a number of stations on the lakes, at some of which records had already been kept by the United States engineers, and made measurements of the mean level extending over a period of twenty years or so. The stations which were thus compared with one another are shown in Fig. 145, and the table on page 404 gives the result of the measurements.

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[1] G. K. Gilbert, "Recent Earth Movement in the Great Lakes Region," U.S. Geol. Surv. *18th Ann. Rep.* part ii. p. 601 (1897).

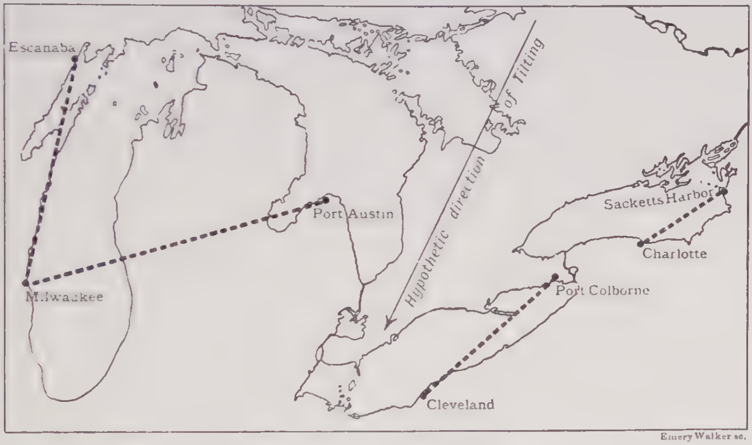

FIG. 145.—Map of the stations used by Gilbert in determining the recent rate of tilting in the Great Lakes. (After Gilbert.)

In drawing his conclusion from these results Gilbert says: "In the discussion of the data used in comparing the several pairs of stations it has been found that, taken at their face value, they indicate a tilting in the hypothetic direction, but it has also been found impossible to resolve all doubts as to the stability of the gages and benches and the accuracy of the measurements. By reason of these doubts the result from no single pair of stations is conclusive, but when assembled they exhibit a harmony which argues strongly for their validity. As tabulated, there are four results, but these are not all independent, since observations and measurements at Milwaukee are used twice. There are, however, three results wholly independent, and a fourth partly independent. To these may be added a fifth, partly independent, namely, the determination of change between Port Colborne and Cleveland for the shorter period 1872–1895. Not only do all these results indicate a change of the same sort, but they agree fairly well as to quantity. The computed change for 100 miles in a century ranges only from 0·37 to 0·46 foot, and the greatest deviation of an individual result from the mean of four is 12 per cent. This measure of harmony appeals strongly to the judgment."

Pairs of Stations.	Direct Distance.	Distance in Direction S. 27 W.	Interval between Dates of Measurement.	Change in Relative Height.	Change per 100 Miles per Century.	Probable Error of Quantities in last Column.
	Miles.	Miles.	Years.	Feet.	Feet.	Feet.
Sackett's Harbour and Charlotte	88	76	22	0·061	0·37	0·18
Port Colborne and Cleveland .	158	141	37	0·239	0·46	0·11
Port Austin and Milwaukee . .	259	176	20	0·137	0·39	0·69
Escanaba and Milwaukee . .	192	186	20	0·161	0·43	0·06
Mean					0·41	. .
Weighted mean					0·42	±0·044

Gilbert is of opinion, however, that it is safer to regard the final mean result as only indicating the order of magnitude of the change. Moreover, he was not aware, at the time the computations were made, of the apparent absence of any tilting in the southern parts of Lakes Michigan, Huron, and Erie, since the formation of the Algonquin beach. Going on the very natural assumption that the rate of tilting was uniform over the whole region of the lakes, he drew an alarming picture of the possible future transference of the outlet from Port Huron to Chicago, the consequent submergence of Chicago, and the practical drying up of Niagara. The recent discoveries in connexion with the so-called hinge-line of the Algonquin beach, however, afford good reason for supposing these fears to be groundless. The region to the south of this hinge-line seems for a long time past to have been quite stable, and both the Port Huron outlet and the Chicago Pass lie within this area.

CHAPTER XVIII

THE ISOSTATIC THEORY OF THE QUATERNARY OSCILLATIONS OF SEA-LEVEL

Jamieson's theory—Meaning of the term Isostacy—Isostatic depression beneath load of sediment—The continents—Association of raised beaches with glacial centres—Isostatic effect of Lake Bonneville—Attraction—Woodward's estimate of the elevation due to attraction—Its inadequacy—Delay in isostatic recovery—Wave-like progression of the uplift—Importance of the lag or residual effect—General lowering of sea-level owing to building up of ice-sheets—Explanation of the absence of raised beaches round the margin of the maximum glaciation—Nature of the submerged forest oscillation—Rise of the sea-level in late-glacial and post-glacial times—Rise of the land within the isostatically depressed areas—Explanation of the Scandinavian phenomena by a combination of these two effects—Application to the British Islands—Difficulty in connexion with the 100-foot beach—Importance of the preglacial shore-line as a criterion for discriminating temporary and permanent deformations of the crust—The preglacial shore-line of Western Scotland—North America—The so-called hinge-lines in the Great Lakes region.

The theory of Isostacy.

The theory of Isostacy was first put forward by Jamieson in the year 1865 [1] to account for the presence of elevated marine sediments of late-glacial age round about the Scottish centre of glaciation. He considered that the flexibility of the earth's crust was so great that it sank beneath the weight of the ice, and so became temporarily submerged, rising again on the melting away of the ice-sheet. The idea has been keenly taken up by the Scandinavian and American geologists, and applied by them with remarkable success to the problems of their own countries. The term isostacy as applied to Jamieson's conception is of much later introduction, and covers a wider field. Stated more generally, the theory implies that there is a certain amount of hydrostatic balance between the different elements of the earth's crust, so that if an additional load be imposed on any portion of the surface, it must necessarily sink, and the remainder of the surface rise, until equilibrium is re-established. Examples of such loads are to be found in the accumulations of sediment round the mouths of the great rivers. Evidence has been brought forward to show that the coasts in the neighbourhood of the delta of the Mississippi are undergoing gradual depression. Indeed it is hard to conceive how the great thicknesses of sediment found locally in certain geological formations could ever have been deposited unless the elevation of the surface by the addition of material were compensated in some way by subsidence. Another application of the idea of isostacy ascribes to the substratum of the continents a less density than that possessed by the substratum of the oceans. It is hard to imagine how otherwise to account for the differences of elevation, unless we are prepared to admit that the earth has an almost inconceivable rigidity. The compensation beneath the continents was at one time thought to have been established directly by geodetical measurements, but the results have since been criticised.

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[1] T. F. Jamieson, "On the History of the Last Geological Changes in Scotland," *Quart. Journ. Geol. Soc.* vol. xvi. p. 161 (1865).

Association of raised beaches with glacial centres.

In the question of the isostatic depression beneath the ice-sheets we are, however, dealing with a more satisfactory problem. The mere association of raised beaches with the three great Quaternary glacial centres in the northern hemisphere supplies us at the start with a very good argument in favour of the theory. Scandinavia, Scotland, and Canada all have their systems of warped shore-lines, which rise higher and higher on the land as the centres of dispersion are approached. The connexion appears even more strikingly when we compare the form of the ice-sheet of Northern Europe at the stage of the Baltic moraine with the course of the

Depression of the Bonneville Basin.

isobases of the late-glacial depression of this area (Fig. 41 and Plate XVIII.). Moreover, raised beaches occur in Greenland, Spitzbergen, and the Antarctic Continent, and they seem also to have been formed in connexion with the Quaternary glaciation of Patagonia. One other case is known in which it has been possible to trace the effect of a temporary load on a portion of the earth's crust. The case is that of Lake Bonneville, which occupied the Great Basin during the Ice Age. Gilbert has shown[1] that the shore-lines of Lake Bonneville are considerably higher on the islands in the centre of the lake than at its margin. By taking a number of altitudes he was able to draw isobases exhibiting the form of the deformation. These are shown in Fig. 146. The added load in this instance was the actual weight of water in the basin, which appears to have had exactly the same effect in depressing the earth's crust as the great ice-masses which occupied the country farther north.

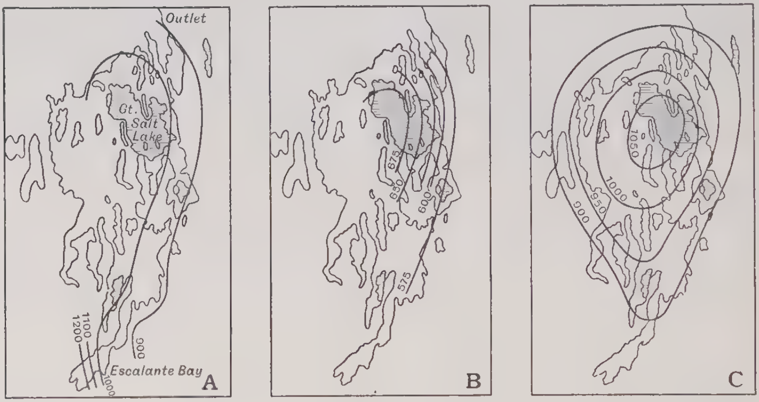

Fig. 146.—Sketch maps showing the isostatic deformation of the Bonneville Basin. (After Gilbert.)

A. Deformation of the Bonneville shore-line. B. Deformation of the Provo shore-line. C. Theoretic curves of deformation of the Bonneville shore-line, constructed from (A) by ignoring the abnormal heights in Escalante Bay, supposed due to faulting. The black lines are isobases, and the recent lakes are shown by shading.

It is not yet perfectly clear, however, that we are quite safe in ascribing all this to isostacy. There is still another means by which it is possible to explain the association of warped shore-lines with the former existence of temporary loads on the earth's surface. If we suppose that the crust is rigid and does not sink beneath the load, then the latter is so much added mass and exerts a very considerable attractive effect on the water bodies in the neighbourhood of its margin. Fig. 147 shows diagrammatically, and of necessity with much exaggeration, the manner in which an ice-sheet may produce elevated and tilted shore-lines round its margin, in the first place by attraction, and in the second by isostacy. In the case of isostacy the water level is

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[1] G. K. Gilbert, "Lake Bonneville," U.S.G.S. *Monograph.*

Theory of attraction.

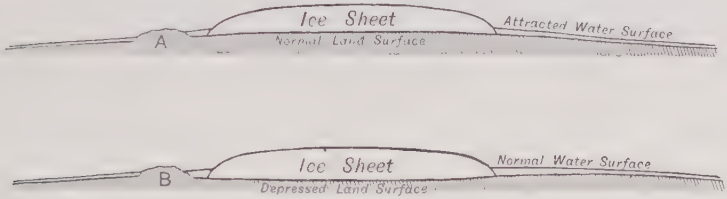

FIG. 147.—Diagram showing the effects of attraction and isostacy.

(1) Attraction: A. Land upon which the tilted water surface is recorded as a raised shore-line. (2) Isostacy: B. Depressed land upon which the normal water surface becomes recorded as a shore-line which is elevated on recovery.

supposed to remain unaltered while the land around the ice is partially depressed beneath it. Shore-lines are cut on the depressed land, and when the ice melts away the land returns slowly to its former elevation, and raises the shore-lines along with it. According to the attraction hypothesis the land remains fixed, but the water is drawn up around the margin of the ice and so enabled to cut shore-lines, which are finally abandoned when the ice disappears and the water sinks back to its former level. Of course these two effects might be supposed to be in operation together, but they are clearly complementary to one another. If the isostacy is perfect, the excess of mass in the ice is compensated by the defect of mass in the crust due to the depression, and there is no attraction. On the other hand, if the earth is presumed to be perfectly rigid, there is no isostacy, but the attraction effect reaches its maximum. In any intermediate state of affairs it is clear that the greater the isostacy the less the attraction, and *vice versa.*

Estimate of the effect of attraction.

Fortunately it has been found possible, by considering ideal cases, to arrive at some conception of the extent to which the attractive effect of an ice-sheet might raise the sea-level along its margin, and also of the slope which the tilted water plane might assume. The quantities arrived at show that the effect of attraction is quite inadequate to explain the observed phenomena. R. S. Woodward [1] has calculated the effect, in distorting the sea-level, of circular ice-caps of 38° angular radius, 10,000 feet thick in the centre, and of various external forms. This hypothetical ice-cap is of course a good deal larger than any which existed in Quaternary times, but it is approximately the size for which the elevation of water surfaces along the margin is a maximum. It thus has the advantage of affording a superior limit. Taking from Woodward's table that one of the assumed forms which seems to represent most nearly the observed conditions on the Greenland Ice-sheet, we find that the calculated elevation along the margin is 347 feet, and the average slope per mile of the disturbed water surface within 1° or 69 miles of the border of the ice-mass is ·4 feet. In the extreme, but of course impossible, case of an ice-sheet of the uniform thickness of 10,000 feet right out to the margin, the figures are 573 feet and 1·0 foot per mile. These figures are proportional to the axial thickness, so that if we wish to regard the ice-sheet as having been 20,000 feet thick we merely double them, if we consider 5000 feet a more likely figure we halve them, and so on.

Its inadequacy.

Now the tilting of the Algonquin shore-line within 1° or 69 miles of the ice-margin varies from 3 feet to 5 feet per mile, and it is quite obvious from the figures quoted above that on no reasonable estimate of the thickness of the ice can we get any result approaching this by attraction alone. To produce such an effect an ice-sheet of normal shape and about the size of that which covered North America in the Quaternary Period would have to be something like 15 miles thick, and this is quite outside the range of probability.

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[1] R. S. Woodward, "On the Form and Position of the Sea-Level," U.S.G.S. *Bulletin*, No. 48 (1888).

The adequacy of isostacy.

It is therefore perfectly justifiable to assume that the raised and warped shore-lines of Scandinavia, North America, and the other glacial centres were not produced by ice attraction. We may now return to the theory of isostacy with a fair amount of confidence and consider to what extent it explains the observed facts in connexion with the late Quaternary submergence around the glacial centres. As regards the adequacy of isostacy to produce the observed effects there need be no doubt. It all depends on the extent to which equilibrium is re-established by the sinking of the earth's crust under the load. In the case of perfect isostacy there ought to be a depression equal to about one-third of the thickness of the superincumbent ice.

Delay in isostatic recovery.

For the production of raised beaches and tilted shore-lines in the regions outside the greatest extension of the ice it is obvious that the depressed area must extend beyond the ice-margin, as in Fig. 147. It is exceedingly likely that there is such an effect due to the partial rigidity of the crust, but it is not a matter of any great importance for the present discussion, because, for a reason which will be mentioned later, the shore-lines formed outside the ice-sheets, during their greatest extension, are probably now submerged and so unobservable. The visible glacial shore-lines are all well within the glaciated area, near the glacial centres. It is a great deal more to the point to consider whether complete recovery from the depression follows immediately on the retreat of the ice or whether there is any residual effect or lag. There seems every reason to believe that there is a very marked delay in recovery. The shore-line of Lake Nipissing (see p. 398), which was a good distance from the contemporaneous ice-margin, has at the present day a very considerable tilt, and Gilbert's observations on the present level of the lakes (see p. 402) seem to show that the warping has continued down to the present day, long after the complete disappearance of the ice. Hansen has proved a similar recent elevation and tilting of the land in the Baltic, north of Stockholm.[1] Both these observations of recent warping have been made in almost tideless waters. It would be absolutely impossible to carry out equally accurate measurements on the coasts of Norway and North America or in Scotland. The two cases available, however, afford very good grounds for believing that complete recovery from temporary isostatic depression is invariably a very slow process. This, however, does not apply to the initial stages of recovery, which appear to have been fairly rapid. Most of the warping in the American lakes took place between the Algonquin and Nipissing stages (see p. 396), and this period must have been brief in comparison with post-Nipissing time. Moreover, good evidence has been brought forward by Brögger (see p. 334) to show that the recovery in the Cattegat progressed with a wave-like motion from south to north, the uplift at any stage having been in the south always considerably more advanced than in the north. It would appear, therefore, that recovery from isostatic depression sets in very soon after the removal of the load, proceeds at first with relative rapidity, but ultimately slows down and reaches its completion only after a considerable lapse of time.

It is this lag or residual effect which is the active agent in the production of tilted shore-lines round glacial centres. In this way the very considerable depression in the heart of the ice-sheet, where it is thickest, comes into play, and the isostatic theory of these shore-lines is not left dependent on the possibly negligible depression outside the attenuated margin. There is, however, another effect of glaciation which up to the present we

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[1] A. M. Hansen, "Skandinaviens Stigning," *Norges Geol. Undersogëlse*, No. 28. Christiania, 1900.

General lowering of sea-level as a result of glaciation.

have not taken into consideration. This is the effect which the building up of huge ice-sheets such as existed in Pleistocene times must have had in lowering the general level of the sea. The building of Woodward's hypothetical ice-cap of 38° angular radius, and axial thickness 10,000 feet, would, for instance, necessitate the removal from the ocean of sufficient water to lower its general level all the world over by 1060 feet. Woodward's ice-cap was, however, far bigger than any individual ice-cap of which we have evidence. The figure 1060 is therefore only of theoretical interest. Fortunately it is not difficult to arrive by calculation at an approximation to the water content of the Quaternary ice-sheets, and so gauge their effect on the general sea-level. This has been done by Penck,[1] whose figures we shall now quote. He estimates the area of the Quaternary ice-sheets of the northern hemisphere at 490,000 square miles,[2] of which 380,000 miles covered what is now land, and the remaining 110,000 miles occupied the basins of shallow seas such as the Baltic and the North Sea. This area is 7·5 per cent of the total area of the ocean. The thickness of the ice is more difficult to arrive at. Penck assumes an average thickness of 1000 metres (= 3280 feet), a very moderate estimate indeed. The mean depth of the sea is reckoned at 3500 metres, so that the thickness of the ice is $\frac{2}{7}$ of the depth of the sea. Taking the specific gravity of the ice as ·9, we find that the Quaternary ice-masses were equal to $7·5 \times \frac{2}{7} \times ·9$ per cent $= 1·9$ per cent of the mass of the sea. The removal of this percentage of the water of the sea would imply a lowering of the surface of $1·9 \times \frac{1}{100} \times 3500 = 66·5$ metres, or, roughly, 210 feet. This result is of course proportional to the average thickness of the ice assumed in the first instance. If we prefer to regard it as having been 2000 metres (= 6560 feet) thick, we get an equivalent lowering of the sea-level of 420 feet. If we consider 1000 metres too great and take instead 500 metres (= 1640 feet), we get 105 feet as the lowering of the sea-level; and so on. The displacement of water over those parts of the sea which were occupied by ice does not appreciably affect the result on account of the shallowness of these seas.

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[1] Albrecht Penck, "Schwankungen des Meeresspiegels," *Jahrbuch der Geographischen Gesellschaft zu München*, Bd. vii.

[2] Geographical miles.

Absence of raised beaches at the outer limit of glaciation.

This effect of glaciation in lowering the general level of the sea at once affords an explanation of several remarkable facts which have been brought out in the preceding chapters. It shows us, for instance, why there are no raised beaches or warped shore-lines along the margin of the maximum glaciation. The general lowering of the sea-level in consequence of the enormous masses of ice in existence at this stage quite overcame the isostatic and attraction effect along the margin of the ice. It was not until the ice-sheets had shrunk considerably, and a large proportion of the abstracted water had been returned to the sea, that the relatively large depression under the thick central portions of the ice-sheet became greater than the general lowering of the sea-level and submergence thus resulted. This theory also affords an explanation of a remarkable result obtained by Brögger in the Christiania region. Here, as has been explained in Chapter XV., the sea at first rose upon the land along the ice-front as the latter retreated. The rise of the sea-level in consequence of the melting of the ice-sheets was at this stage beating the isostatic recovery. It was not until the ice had retreated a little further, and the recovery got well started, that the emergence recorded by the various shore-lines commenced.

Explanation of the Christiania submergence.

Explanation of the preglacial emergence.

It will be remembered also how, in connexion with the preglacial shore-line of Southern Britain (Chap. V.), an emergence set in some time before the oncoming of the ice, and allowed of the formation of blown sand and head upon the surface of the beach. This emergence was no doubt the first indication in these regions of the existence of the growing ice-sheets of the north, which ultimately spread down and covered up the beach itself.

In estimating the possible amount of this effect,

Effect of the Antarctic Ice-sheet.

however, no account has been taken of the glaciation of the southern hemisphere. Here we are confronted with a difficulty because we do not know if the glaciation of the two poles was contemporaneous. It will be interesting, however, to consider the magnitude of the quantities involved. The Antarctic Ice-sheet of the present day has an area of about 4,500,000 square miles.[1] This is comparable with the extent of the Quaternary ice-sheet of North America, so it is not unreasonable to assume the same average thickness of 1000 metres. Calculating as before, we get a volume of ice equivalent to a lowering of the sea-level of about 40 metres or 130 feet. It makes a good deal of difference to our argument whether this water was tied up as now in the ice-sheet or set free to raise the level of the sea during the glaciation of the northern hemisphere. If it was entirely set free, as Croll supposed (see p. 324), it would reduce the change of level (calculated on the basis of 1000 metres of ice) from 210 feet to 80 feet.

The geologists of Shackleton's expedition,[2] however, have brought forward evidence to show that the Antarctic Ice-sheet in the Ross Bay region was formerly more extensive than now, and at least 2000 or 3000 feet thicker. This increase might produce an extra lowering of the sea-level of anything from 50 to 150 feet. To this must be added the effect of the glaciation of Patagonia, which is as yet not very well known.

At present it is futile to go much further than this in speculating on the effect of glaciation in altering the sea-level, except perhaps to point out that the above figures show that if the great Quaternary ice-sheets of the world were contemporaneous, a lowering of sea-level of about 400 feet is to be expected, on the assumption that the ice-sheets were on the average 3280 feet thick. Moreover, if a greater average thickness is considered more probable, then the effect on the sea-level must be regarded as proportionally greater.

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[1] The ice-sheet at the south pole must, according to Shackleton's results, have an altitude of about 10,000 feet, but the geologists of the expedition are of opinion that the horizontality of the Beacon sandstone in the coastal mountains indicates that this range is merely the exposed edge of a plateau which extends in under the ice-sheet. The latter may thus be of no great thickness. It is improbable, however, that a plateau 5000-8000 feet high extends over any great part of the Antarctic continent. At any rate, 1000 metres is not an enormous over-estimate for the thickness of the ice, as there must be many large valleys and depressions. See *The Heart of the Antarctic*, vol. ii. p. 290 (1909).

[2] *The Heart of the Antarctic*, vol. ii. pp. 276-277 (1909).

The reader will now no doubt have a clear conception both of the nature and approximate magnitude of the two factors with which it is proposed to explain the Quaternary oscillations of sea-level. One of these factors, the depression of the sea-level, has been shown to be an absolutely necessary result of glaciation. The other factor, the isostatic depression, has attached to it a very high degree of probability, since, in all of the cases known to us in which a temporary load has been imposed on the crust of the earth, the phenomenon of warped shorelines is observable. The theory is not merely an inference from the observed facts, but an *a priori* deduction which is shown to meet these facts at almost every point. In this respect it has a distinct advantage over any attempt to explain the facts by deformations of the earth's crust of the nature of folding and faulting. The various regions will now be considered in detail, and an attempt made to bring out clearly the points for which the theory affords an explanation as well as those which are still obscure.

Cause of submerged forest oscillation.

Now, in order to understand the complicated relations of the land and sea in Northern Europe during the Quaternary, it is important in the first place to realise thoroughly the nature of the oscillation which allowed of the growth of the submerged forests. This oscillation, which occurred in the period between the Yoldia and Littorina Seas, and also between the late-glacial and early Neolithic submergences in Scotland (see p. 377), was responsible for the cutting off of the Baltic from the ocean, whereby it was converted into the Ancylus Lake. In the fact that the submerged forests have been proved over a wide area, almost the whole of North-western Europe, they differ essentially from the raised beaches which are grouped round the glacial centres. The widespread character of the oscillation, which appears also to have affected North America (see p. 425), is good ground for assuming that it was caused by a general lowering of sea-level. This, according to our theory, must have been brought about by a recrudescence of some one of the ice-sheets, possibly that of the Antarctic Continent. When this ice-sheet melted again the sea rose once more, and appears to have been rising slowly since. Now in thinking of the effects of this oscillation we must conceive of it as referred to an ideal sphere of unalterable radius concentric with the earth and not to the land, which, within the depressed areas, was moving itself. Referred to this ideal sphere the motion of the sea-level in glacial and post-glacial time passed through the following phases—

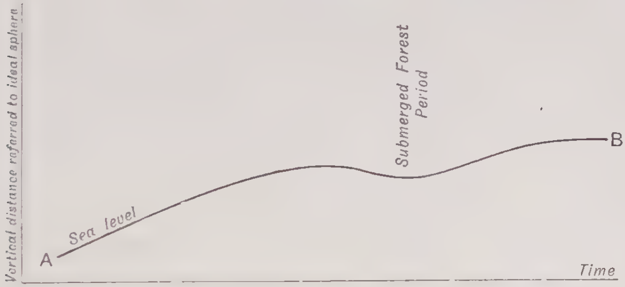

FIG. 148.—Curve showing the supposed oscillation of sea-level in north-western Europe since the retreat of the ice-sheet.

(1) Low sea-level during Glacial Period.
(2) Rise owing to melting of ice-sheets.
(3) Fall owing to recrudescence of some ice-sheet (submerged forests).
(4) Rise owing to remelting of same ice-sheet.

This motion of the sea is expressed as a curve in Fig. 148, in which the ordinates represent vertical heights, and the horizontal distances time. This curve represents correctly the motion of the sea with respect

Combined motions of land and sea.

to the land outside the areas affected by the isostatic depression, but not within them. Within these areas we have to consider the effect of the rise of the land, which was at first slow, then more rapid, and finally slower again (see p. 412). In Figs. 149 and 150 this motion is represented by the line CD, the rise being, of course, greater and the curve steeper in the central areas, the history of which is that of the northern Christiania district north of the isobase through the Mjösensee (see p. 338). The line AB in these figures represents the motion of the sea transferred from Fig. 148, both motions being, of course, referred to the ideal sphere just mentioned. Now a moment's thought will make it clear that the change in the vertical distance between the curves AB and CD represents the relative motion of the land and sea. Where the curves are diverging the land is emerging; where they are converging the land is becoming submerged; where they are parallel the relative level of land and sea is undergoing no change, and there is in consequence a tendency towards the formation of well-marked shore-lines.

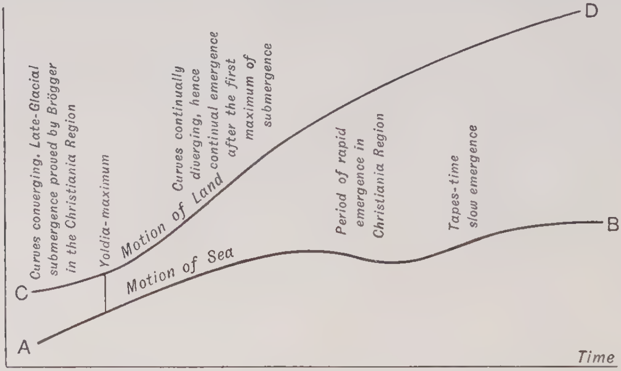

FIG. 149.—Curves showing the absolute and relative motions of the land and sea in the central isostatically affected areas since the retreat of the ice.

Central Scandinavian district.

Let us consider first the central area which is represented in Fig. 149. On the left of the figure the isostatic recovery has not got properly started, while the rise of the sea-level is in full swing. The curves are approaching one another. This represents the submergence proved by Brögger to have followed, in the Christiania region, immediately upon the retreat of the ice-margin (p. 330). Soon, however, the curves become parallel. This is the Yoldia maximum. They then diverge for a while slowly, representing slow emergence. This is the period of deposition of the late-glacial shell-banks, representing 0-40 per cent of the uplift (p. 334). There follows then for a time a rapid divergence, representing rapid emergence of the land. This is the period which in the Christiania region is represented by very few shell-banks, *i.e.* 40-66 per cent of the uplift (see p. 336). Next there comes an interval of slow divergence of the curves, representing slow emergence. This is represented by the upper Tapes banks, corresponding to 60-85 per cent of the uplift (p. 334). Finally, the emergence quickens up a little in the time of the lower Tapes banks, 85 to 100 per cent of the uplift.

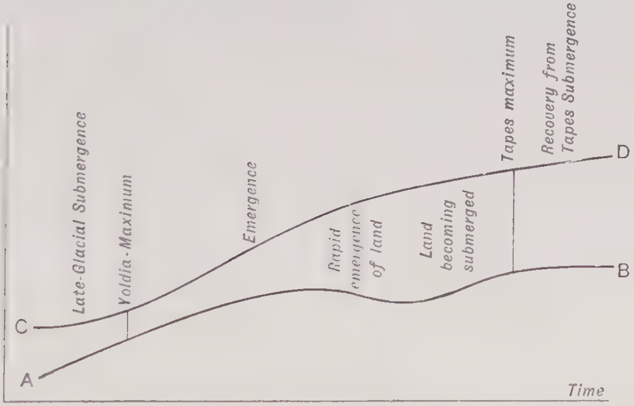

FIG. 150.—Curves showing the absolute and relative motions of the land and sea in the marginal isostatically affected areas since the retreat of the ice.

Peripheral district.

Now let us turn to Fig. 150, representing the history of the peripheral district, south of the Mjösensee zero line in the Christiania region. The story is the same until the maximum of the submerged-forest depression of sea-level is passed. There then comes a difference, however, for the curves are converging. This represents the Littorina-Tapes submergence of the peripheral regions. The curves soon cease to converge and become parallel; this is the Tapes maximum. They then diverge slightly, representing the recovery from the Tapes submergence.

The two districts compared.

Now the only difference between this figure and the last is in the gentler slope of the upper curve, representing the necessarily smaller and slower elevation of the land in the peripheral region of the isostatically depressed area, yet this introduces an important difference in the relative motion of land and sea. In the first case there is a continuous, though irregular, emergence after the maximum of the Yoldia submergence. In the second this emergence is interrupted by a submergence. The so-called Littorina-Tapes depression is therefore not a depression of the crust in the true sense, that is with reference to the ideal sphere of constant radius. The crust was rising all the time, and the shore-line of the Littorina-Tapes maximum was cut at the period when the sea was rising at the same rate and so became for a while stationary on the land.

The peculiar merit of this theory is that it starts with two simple *a priori* conceptions, both in themselves inherently probable and supported by evidence in other areas, and by combining them explains an extremely complex series of changes in the relative level of land and sea.

The isostatic phenomena of Britain similarly explained.

We shall now pass on to the consideration of the British Isles. Here we have the following sequence of events (see p. 361)—

(1) A late-glacial submergence centring in the Scottish Highlands, shown by the 100-foot beach and the late-glacial marine clays.

(2) A period of general low sea-level proved by the submerged forests.

(3) An early Neolithic submergence centring in the Scottish Highlands and shown by the so-called 25-foot beach.

This is exactly similar to the history of the peripheral regions of Scandinavia, and admits no doubt of a similar explanation. The story is, however, less complete. There is no evidence to show that the sea rose on the land as the glaciers retreated—there could be no such evidence within the limited range of 100 feet between the late-glacial and present sea-levels. All we know is that at some period shortly after the retreat of the ice the sea stood at the 100-foot level. There was then recovery marked by lower shore-lines—those about the 50-foot level. Then apparently the sea was lowered and the submerged forests enabled to grow. The return of the sea found the recovery from the glacial depression still incomplete, and the Neolithic beach was formed at the period when the sea and land were rising at equal rates, just as in the case of the Littorina-Tapes shore-line. Finally the recovery beat the rise of the sea, and so the Neolithic beach was raised to its present level.

Difficulty of the 100-foot beach.

There are, however, complications in the British area which are not met by the theory. The 100-foot beach is an especial puzzle. It seems to have, as indicated in Fig. 151, a very limited area of distribution, much more limited than that of the Neolithic beach. It maintains, as far as available measurements go,[1] an approximate horizontality within this area, and when it disappears it does so abruptly, not sinking gradually beneath sea-level as the Neolithic beach does. For instance, on the coasts of Sutherland and Caithness in the extreme north-east of Scotland, the beach is seen for some distance finely developed at the 100-foot level. There is then an interval of high cliffs, now being undercut by the sea, and north of this a district with smooth boulder-clay slopes descending gradually to near sea-level and without even a trace of marine erosion. The 100-foot beach absolutely disappears in the interval. The isostatic theory in its simple form will of course not assimilate facts of this kind. It would seem as if nothing but faulting could explain the anomaly. Possibly there has been some post-glacial faulting here. Possibly more careful investigations will reveal some other reason why the beach should appear to stop suddenly at certain points on the Scottish coasts.

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[1] These measurements were made mainly in the peripheral area and are of small number and no great accuracy.

Importance of the pre-glacial shore-line.

In dealing with the isostatic problems of the British Isles, the pre-glacial shore-line described in Chapter V. is of primary importance. It is a datum to which subsequent oscillations of the shore-line may be referred, and, as such, affords a criterion for the discrimination of temporary and permanent deformations of the crust. A permanent glacial or post-glacial deformation must show itself as a difference in level between the pre-glacial and present shore-lines. On the other hand, a temporary

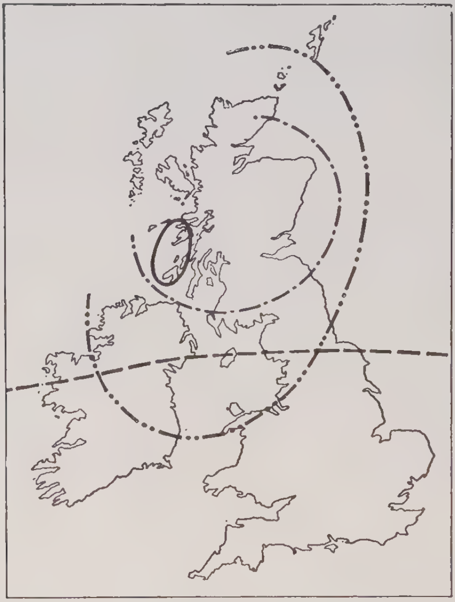

Fig. 151.—Diagram to show the distribution of the various beaches in the British Isles as at present known.

——— Pre-glacial beach of the Western Isles of Scotland.
· — — Northern limit of pre-glacial beach of Southern Britain.
— · — · — 100-foot late-glacial beach of Scotland.
—··—··— Post-glacial, Neolithic beach, so called 25-foot raised beach.

oscillation, if complete, leaves no record of this kind, although it may be readily demonstrable in other ways. Now this pre-glacial shore-line has been observed in numerous localities south of a line through Yorkshire, the Isle of Man and Mayo. It has been traced almost continuously for long stretches along the southern coasts of Ireland, Wales and England, and occurs also on the coast of France. Throughout the greater part of this district it stands uniformly some 10 or 12 feet above the present high-water mark, and maintains a remarkable parallelism with the present sea-level. This parallelism proves almost beyond a doubt that no marked permanent deformation by folding or faulting has taken place over this wide area since pre-glacial times. The glacial and submerged forest depressions of sea-level, which affected this area, were clearly of a temporary nature, for the sea has returned to almost the same level which it occupied in pre-glacial times. This is an additional piece of evidence in support of the hypothesis that these oscillations were due to the binding up of water in the ice-sheets.

Behaviour of the pre-glacial shore-line in the isostatically depressed areas.

Now it is clearly a matter of great importance to find out what happens to this pre-glacial beach, when it passes into the area of the post-glacial raised beaches. Up to the present, however, very little has been effected in this direction. Some significance may attach to the fact that the pre-glacial shore-line is slightly lower in Yorkshire and the Isle of Man than further south. In Yorkshire the inner angle of the pre-glacial platform lies a few feet above high-water mark, in the Isle of Man approximately at high-water mark. The former of these localities lies a short distance outside the area of distribution of the so-called "25-foot" or early Neolithic raised beach, the latter fairly well within it (see Fig. 151). This may possibly be an indication that towards and within the area of the post-glacial raised beaches the pre-glacial shore-line has suffered a depression from which it has as yet not quite recovered. Its apparent absence over the greater part of Scotland might therefore be due to its being entirely below sea-level and thus unobservable.

Throughout a small area in the west of Scotland,[1] however, there is a well-developed pre-glacial shore-line at a level of 100 to 135 feet above high-water mark (see Fig. 152). This may be tentatively correlated with the pre-glacial shore-line of Southern Britain. If so, how has it become elevated in this district? Its known area of distribution is embraced within that of the late-glacial 100-foot beach, the anomalous behaviour of which we have described above. It is just possible that its elevation may be in some way connected with that of the 100-foot beach. Speculation on this question is at present of little use. It is felt that any explanation which might be offered would hardly inspire confidence. All that can be safely said is that we appear to be dealing with some effect superimposed on those of isostacy and oscillation of the sea-level.

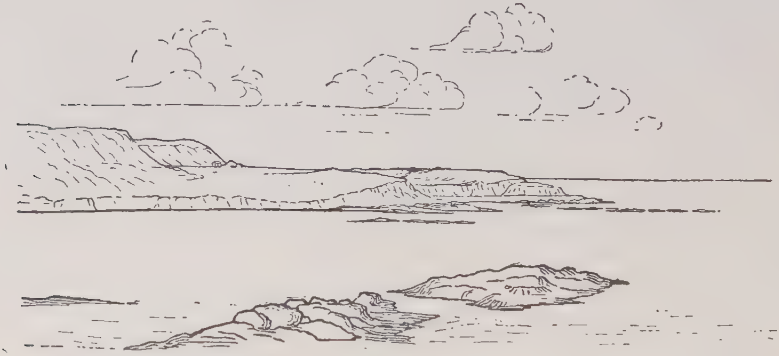

Fig. 152.—The rock platform and cliff of the pre-glacial raised beach at Uragaig in Colonsay, one of the Western Isles of Scotland.

Isostatic phenomena of North America.

Finally, passing on to the consideration of North America, we find that so little is known of the oscillations of sea-level that it is impossible to trace out in detail the applications of the theory. We know that there was a late-glacial submergence, the Champlain Period. It does not seem, however, to have been proved here, as in Norway, that the sea at first rose on the land as the glaciers retreated. No doubt, if it was the case, it could be proved, for the amplitude of the oscillation is quite sufficient. Submerged forests have been observed at the head of the Bay of Fundy and at other points on the coast of New Brunswick,[1] proving a period of low sea-level in post-glacial times as in north-western Europe. So far there is a correspondence. I know of no record, however, of any raised beach which might correspond to the Littorina-Tapes shore-line of Scandinavia or the early Neolithic shore-line of the British Isles. One might venture a prediction that when the oscillations of sea-level are properly studied a shore-line of this age will be discovered, and that, as in Scandinavia, it will represent a distinct resubmergence in the south and a slowing down of the emergence in the north.

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[1] W. B. Wright, "On a Pre-glacial Shore-line in the Western Isles of Scotland," *Geol Mag.* N.S. Decade V. vol. viii. p. 97 (1911).

The so-called hinge lines.

Some peculiarities in the region of the Great Lakes call for further discussion. The northern limits of horizontality of the beaches of Lakes Chicago, Maumee, and Whittlesey (p. 393), and of Lake Algonquin (p. 396) have no immediately obvious explanation on the basis of the theory of isostacy. Goldthwait regarded these so-called hinge-lines as lines of weakness in the earth's crust, each of which formed a sort of joint about which the tilting took place. It must not be forgotten, however, that the change from horizontality to gentle, and finally to steeper, tilting takes place perfectly gradually as the lines are crossed. Goldthwait was at first of opinion that his measurements justified the conclusion that further hinge-lines or joints could be detected farther north in the warped shore-lines of the Algonquin Period. Robinson,[2] however, showed that the observations are equally reconcilable with the hypothesis of uniform warping, and Goldthwait in his most recent paper admits the possibility of either interpretation. Hobbs has also maintained the hypothesis of jointing, but it does not seem as if the evidence is as yet quite satisfactory. The existence of the northern limits of horizontality may, however, be regarded as proved, and is certainly one of the most interesting problems connected with the isostatic depression of North America.

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[1] Robert Chalmers, "Report on the Surface Geology of Southern New Brunswick," *Geol. and Nat. Hist. Survey of Canada*, 1890.

[2] H. H. Robinson, "Ancient Water-planes and Crustal Deformation," *Journ. of Geology*, vol. xvi. p. 347 (1908).

CHAPTER XIX

POST-GLACIAL CHANGES OF CLIMATE IN NORTH-WEST EUROPE

Immigration of the Scandinavian flora—The Arctic Period—Its relation to the changes of sea-level—The Birch Period—The Fir Period—Its relation to the Ancylus Period—The Oak Period—Its coincidence with late Ancylus and Littorina-Tapes time—The Beech Period—The climatic optimum—Its date—Former existence of pine forests on the outer islands of Norway—Immigration of the floras of Finland, Denmark, and Great Britain—Former occurrence of forests on the exposed northern and western coasts of Scotland—Date at which the fir, oak, and hazel entered Great Britain—Probable cause of the westward extension of forests—Suggestion that the Littorina-Tapes submergence was the cause of the climatic optimum—*Entada scandens*—Objections to this explanation.

A PERUSAL of the preceding chapters dealing with the complicated post-glacial changes of level in Scandinavia and the Baltic, and a careful consideration of the theory put forward to account for them, will, it is hoped, have left the reader with a fairly clear conception of the succession of these changes and the varying manner in which they affected different portions of the country. This being the case we are now in a position to proceed to the discussion of the variations of climate which can be shown to have occurred while these oscillations were in progress. The advance of our knowledge in this direction has depended very largely on the botanical investigations of the Norwegian Axel Blytt and the Swedes Nathorst, Gunnar Andersson, Sernander, von Post and Gavelin. The mass of evidence bearing on the subject which has been accumulated by these workers, more especially Gunnar Andersson and Sernander, is enormous; but, unfortunately, there is such dissension regarding the ultimate interpretation of the facts, that it is extremely difficult to find out from the literature how far one may safely go in drawing conclusions therefrom. We shall, however, in the following pages make an attempt to do this, and shall commence by giving some account of the immigration of the Scandinavian flora in post-glacial times, following for this purpose the account of Gunnar Andersson.[1]

Immigration of the Scandinavian Flora.

The Arctic Period.

The oldest elements of the post-glacial Scandinavian flora were a number of arctic plants, which established themselves shortly after the retreat of the ice in those parts of the country which lay above sea-level. This arctic flora was first discovered by Nathorst in Scania, and he subsequently studied its distribution over a much wider area. The remains occur in fresh-water clays lying directly on the moraine. They include the following alpine and high northern species:

Dryas octopetala,
Salix polaris,
S. herbacea,
S. reticulata,
Oxyria digyna,
Arctostaphylos alpina,

as well as the distinctly northern species:

Betula nana,
Polygonum viviparum,
Salix phylicifolia.

This arctic flora entered the country from the south-east over the peninsula of Jutland, which must at a fairly early stage have become connected with Scandinavia. It no doubt followed the retreating ice-sheet northward, forming a belt around its margin and bounded on the south by the succeeding Birch Flora. It occupied the country, however, until a fairly late stage in the history of the Yoldia Sea, when the land had to a large extent recovered from its depression and emerged from the sea. In fact, in the peripheral parts of the area covered by the Yoldia Sea the land had actually attained as great an extent as now at a time when the flora was still purely arctic. This has been proved by the finding of the little polar willow, *Salix polaris*, in northern Scania, a little over, and in southern Scania under, the present sea-level in fresh-water clays, which in the former case at least overlie the stratified clays of the late-glacial sea. In Gotland and Estland the same species are also found in relations which show that the land at that time had elevated itself at least half, perhaps two-thirds, of the depth to which the depression had extended. A further link with the geographical development of the country is given by the occurrence in Gotland, in association with these arctic plants and at a height of 28 metres over the sea, of *Zanichellia polycarpa*, a species living in slightly salt water. This shows that at this same period, when from one-half to two-thirds of the recovery from the Yoldia depression had been accomplished, the water of the Baltic, although considerably freshened, was yet slightly brackish, so that the connexion with the Atlantic over lakes Wener and Wetter cannot yet have been entirely severed.

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[1] Gunnar Andersson, *Svenska Växtvärlden's Historia.* Stockholm, 1896.

Its relation to the changes of sea-level.

Following close upon the heels of the arctic flora, and no doubt in places mingling with it, came the birch (*Betula odorata*) and its associate the aspen. These trees formed the first woods in Scandinavia. Remains of birch occur above the arctic bed in the peat-mosses of Denmark and southern Sweden, and in the lower portions of some tufa deposits. Stratigraphical relations, however, seem to show that the time during which the birch and aspen were the only forest trees in the country was very short in comparison with that marked by the predominance of species of trees which immigrated later. The birch woods probably formed a belt round the district occupied by the arctic flora, and were themselves bounded on the south by the succeeding fir woods.

The Birch Period.

The Fir Period.

The immigration of the fir is one of the most strongly marked points in the history of the Swedish flora. A conspicuous layer of fir-stools is to be observed in many of the peat-mosses of Denmark and Scandinavia. It lies, as was first shown by Steenstrup, immediately on that containing the birch and aspen. The fir is now spread over the whole country, but before the advent of the spruce it occupied a much more important place in the flora. Moreover, along with it arrived the main mass of the species composing the present flora. Among the species which entered during the earlier part of the Fir Period are the mountain ash and bird cherry, while its later stages saw the advent of such important trees as the elm, alder, lime, hazel, cornel and hawthorn. With regard to its date, the Fir Period seems to be entirely embraced within the rather ill-defined Ancylus Lake Period. We have seen above that the waters of the Baltic had to a large extent lost their saltness and become brackish during the prevalence of the arctic flora. The connexion with the Atlantic was probably completely severed, and fresh-water conditions established, during the Birch Period. The fir, however, established itself pretty early in the Ancylus Period. It is found associated with the birch in peat and sand layers beneath the beach deposits of the Ancylus Lake in Gotland.

Its relation to the Ancylus Period.

Moreover, the peat-mosses of those portions of Norrland which were covered by the Ancylus Lake show at the base no trace of a northern flora, the remains of fir occurring right down to the base. The fir was therefore well established in Sweden at the Ancylus maximum. Sernander[1] points out that in southern Sweden, where the complete succession occurs, there is evidence which tends to show that the rise in temperature was rather rapid. Thus in the deposits mentioned above as occurring beneath the Ancylus beach deposits in Gotland, Sernander found *Cladium mariscus* almost between the oldest pine-needles. Also Lagerheim and Holst in Scania, and L. von Post in Närke, have shown that pollen-grains of hazel and remains of elm occur in the very lowest beds of the peat-mosses which are underlain by the Dryas clay.

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[1] R. Sernander, "Die schwedischen Torfmoore als Zeugen postglazialer Klimaschwankungen," in *Die Veränderungen des Klimas*, p. 201, Geol. Congress, Sweden, 1910.

The Oak Period.

Although the main mass of the present flora came in with the fir, there yet existed during the Fir Period no tree fit to compete with it in forest making. Such a tree arrived in the oak. In the more low-lying and fertile coastal districts in the south of Sweden it appears to have ultimately occupied the country to the almost total exclusion of the fir, but it probably never established itself thoroughly in the more high-lying unfertile regions. In the flat land of middle Sweden, which was covered by the Littorina Sea, the lower portions of the peat-mosses are found to be composed of an oak zone, in which remains of conifers are almost completely wanting. This oak zone corresponds, however, only with the youngest parts of the oak zone in the peat-mosses of Denmark and south Sweden, for the oak entered southern Sweden in the latest stages of the Ancylus Period. This is proved by several facts, the most convincing of which is its occurrence, along with alder and hazel, in the submerged forests off the coasts of Scania and Denmark. These forests must have grown before the southward transgression of the Ancylus Lake, and its connexion with the Atlantic through the Sound and the Belts, for the ground on which they grew has clearly been submerged ever since. During excavations in the harbour of Ystad, Norsted found, beneath marine sand and gravel, a peat layer, dating from before the maximum of the Littorina depression, which contained remains of oak, alder, maple and some other trees. The Oak Period thus extended from the end of the Ancylus Period well on into Littorina times. It witnessed the advent of the Norway maple (*Acer platanoides*), the ash, the mistletoe and the ivy. Towards the very end of the period certain more continental species, including the lime (*Tilia grandiflora*), the hornbeam (*Carpinus betulus*)

Its coincidence with Late Ancylus and Littorina time.

and the common maple (*Acer campestre*) established themselves in the extreme south of Scandinavia.

The Beech Period.

Last of all came the beech, which is occasionally found in the very uppermost parts of the peat-mosses in Schleswig-Holstein and Denmark. Its remains are rare, however, on account of its avoiding low-lying marshy flats and thus standing less chance of becoming embedded in the peat-mosses. The upper layers in Denmark and Scania are more commonly filled with remains of alder which are very probably the representatives of the Beech Period.

The climatic optimum.

We have now sketched in brief the history of the northward migration of several of the important elements of the Scandinavian flora, and have adduced a number of facts which connect the arrival of certain species with well-defined stages in the post-glacial geographical development of the country. We have hitherto dealt exclusively with the northward migration of the plants. It has, however, been clearly proved that certain species, after reaching their northernmost limit, withdrew again southward, so that their area of distribution is at present somewhat more restricted than it was formerly. This important fact we owe to the researches of Axel Blytt and Gunnar Andersson.[1] Owing to the large number of isolated facts necessary to prove a recession, the investigation has up to the present only been possible in the case of a few common or easily determinable species. The most satisfactory of these is the hazel (*Corylus avellana*), which has been dealt with by Andersson in a special monograph. The results of this elaborate piece of work are summed up in the map (Plate XXIII.), and need not be further described. A recession has also been proved in the case of the water-nut (*Trapa natans*), as shown in Fig. 153. Moreover, an investigation of the present and former tree limit in the mountains of Swedish Lappland has led to a similar result. In this region, the oecology of which has been entirely uninfluenced by

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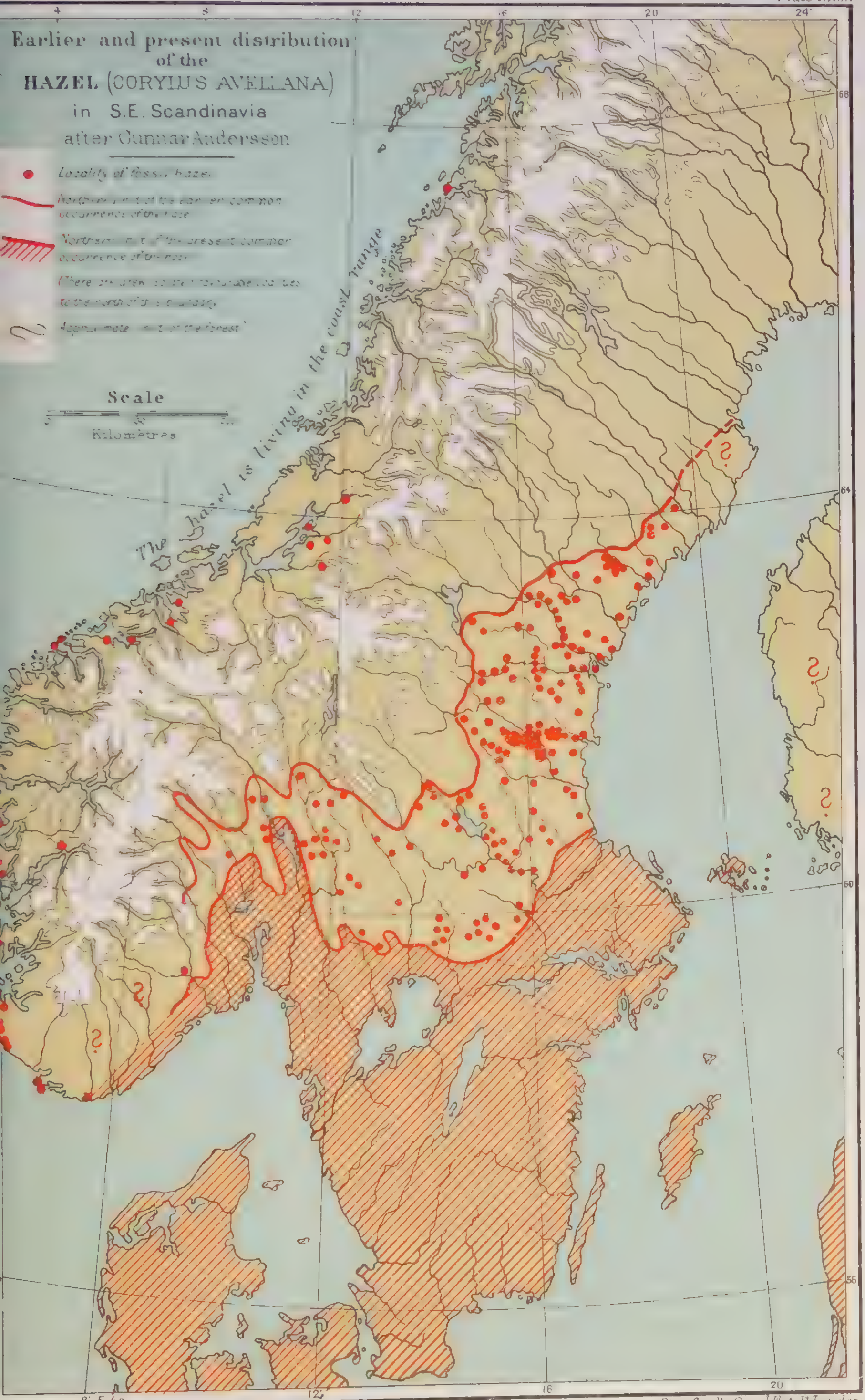
[1] Gunnar Andersson, "Swedish Climate in the Late-Quaternary Period," *ibid.* p. 247.


Earlier and present distribution
of the
HAZEL (CORYLUS AVELLANA)
in S.E. Scandinavia
after Gunnar Andersson
Locality of fossil hazel
Northern limit of the earlier common occurrence of the hazel
Northern limit of the present common occurrence of the hazel
There are a few scattered localities to the north of this boundary
Approximate limit of the forest
Scale
Kilometres
The hazel is living in the coast range
?
4
8
12
16
20
24
68
64
60
56
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man, the pine woods, consisting of fir and spruce, have a pretty definite upper limit. They are succeeded by birch woods, which also have a distinct upper limit, the higher slopes of the mountains being without woods and inhabited only by alpine species of plants. It has been proved by means of the fossil remains that the birch was at one time quite common in the alpine region,

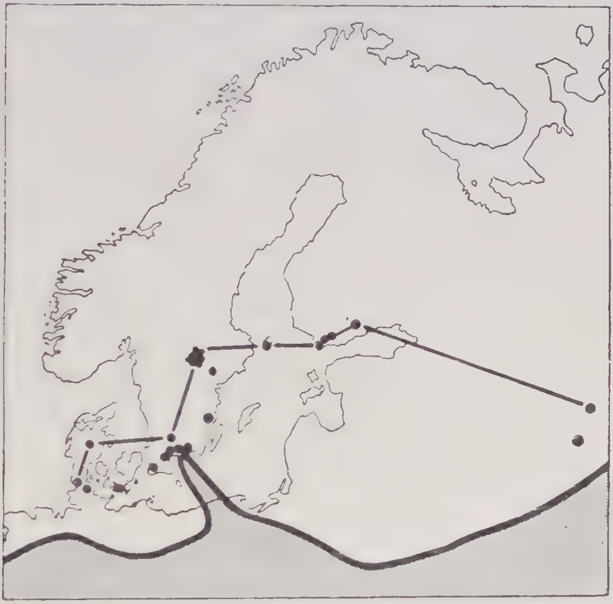

Fig. 153.—Map showing the former post-glacial distribution of *Trapa natans*. The dots indicate fossil occurrences. Within the shaded area the plant is still living in scattered localities. (Some new fossil localities in the south of Finland are not indicated.) (After Andersson.)

while the pine forest extended formerly into both the birch and alpine regions.

These researches show that at a certain stage of post-glacial time the climatic conditions were in some way more favourable to the spread of the above-mentioned species than they are at present. This period of extended distribution is known as the post-glacial climatic optimum. Gunnar Andersson cites several pieces of

Date of the climatic optimum.

evidence which help to define its date in terms of the geographical changes. The occurrence of maple (*Acer campestre*) in the submerged forest of the harbour of Ystad points to its coincidence with late Ancylus time. The same conclusion is to be drawn from the finding of *Trapa natans* in fresh-water mud beneath marine deposits of Littorina age only 2 to 3 metres above the sea at Ronneby. An interesting fact in regard to the hazel seems to show that the subsequent deterioration of the climate went on hand in hand with the recession of the Littorina Sea. In the portions of Norrland which were covered by the Littorina Sea the occurrences of fossil hazel grow fewer and fewer as the height above

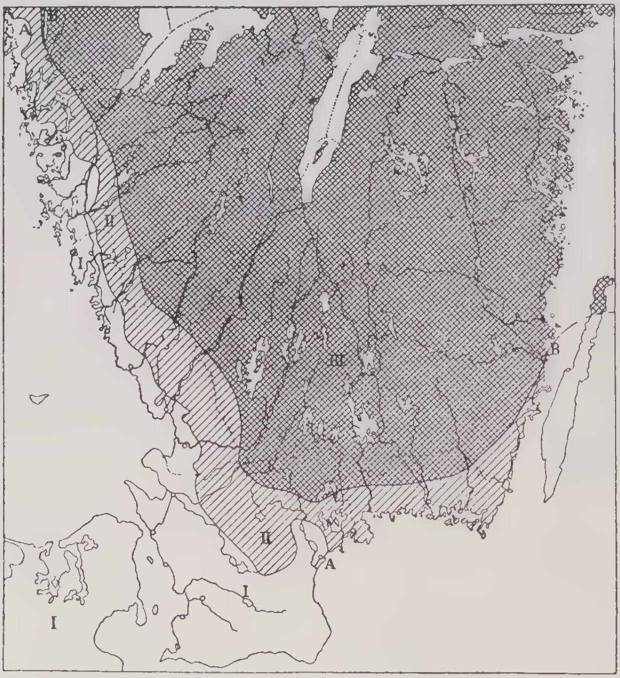

Fig. 154.—Map showing the present southern limit (A-B) of the pine (*Pinus sylvestris*) in southern Scandinavia. (After Andersson.)

In the unshaded area (I) remains of it are found in large quantities in the peat-bogs, but there are no wild living trees. In the lined area (II) the pine forests are degenerate and sickly, but in the cross-hatched area (III) their development is normal and good.

the sea decreases, and they are almost lacking below the 50 m. level.

We have now traced out the post-glacial variations in the climate of Sweden as far as there is any general unanimity in the conclusions of different investigators concerning them. It is clear that the northward advance of the various species after the retreat of the ice indicates a fairly steady amelioriation of conditions up to what we have called the climatic optimum, which happened at the end of the Ancylus and the beginning of the Littorina Period. After that a deterioration of the climate set in. This result has been confirmed by investigations in other countries. In Norway[1] in particular some interesting evidence has been forthcoming. During the last ten years Rekstad, Öyen, and Kolderup have found leaves of genuine arctic plants, especially of *Salix polaris*, in marine terraces near the border of the deepest late-glacial depression in many places on the western and south-western coasts of Norway. Near Christiansand, in marine deposits of about the same age as the Ra-moraines (see p. 118), Danielsen has found remains of *Betula nana*, *Salix polaris*, and other willows, together with a molluscan fauna which is characterised by the presence of *Portlandia arctica*. To the south, on Lister and Jaederen, Holmboe has proved that at some time, while the arctic flora occupied the country, the sea-level lay somewhat lower than at present, for he has found the arctic plants in the bottom layers of a peat-bog some 3 metres below the present surface of the sea.

The arctic flora of Norway and the Yoldia Sea.

With regard to the date of the immigration of the birch into Smålenene, Holmboe has also established an important point. In marine deposits at the bottom of a small peat-bog known as the Svartemyr, 19 kilometres inside the Ra-moraines, he has found remains of the birch (*Betula odorata*), the juniper (*Juniperus communis*), together with a typical birch vegetation in which

Date of immigration of the birch,

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[1] See Jens Holmboe, "On the Evidence furnished by the Peat Bogs of Norway on Post-glacial Changes of Climate," *ibid.* p. 335.

the dwarf birch (*Betula nana*) formed the most marked arctic element. These plants must have lived in the interior of Smålenene at a time when the ocean stood at least 145 metres above its present level and filled the basin of the Svartemyr, *i.e.* at a time when only about 17 per cent of the total uplift of the land had taken place there. Another interesting find by the same investigator gives a later limit for the period of the introduction of the oak into Christiania. In the Ostraea clay of Bakke, in Jarlsberg, 35 metres above the sea, he found the cupula of an acorn. This clay, according to Brögger, was deposited when about 67 per cent of the total uplift of the land had been accomplished.

and of the oak.

Climatic optimum in Norway.

In Norway, just as in Sweden, various plants seem in post-glacial times to have extended farther north and higher up in the mountains than at present. Thus, in the central portion of southern Norway the fir limit once lay 300 metres higher in the mountains than now. What is still more significant is that the occurrence of trunks and stools in the peat-bogs show that in former days vigorous pine forests grew on the exterior islands along the coast which are nowadays quite barren. These forests existed as far north as Ingö near the North Cape, where under the present climatic conditions no forests at all can exist. The occurrence of a post-glacial optimum of climate is also proved and dated by the sections on Jaederen. Here in the marine layers, from the very maximum of the Littorina-Tapes depression, and also in the lacustrine deposits above and below these layers, is found a flora of a more southern type than that which lives in these places at the present time.

Its date.

Immigration of the flora of Finland.

One of the most masterly contributions ever made to the subject is that of Harald Lindberg on the development of the flora of Finland.[1] The exhaustiveness and thoroughness of this fine piece of work tempts one to go into it more fully, but, unfortunately, space only permits of a summary. The order of immigration was much the same as that proved in Sweden, but there are some interesting and important differences. In the whole of Finland arctic plants (such as *Dryas*, *Salix polaris*, and *Betula nana*) of late-glacial age have only been found in one locality, namely, the parish of Kivinebb, in the district between Lake Ladoga and the Gulf of Finland. Here they are associated with a beetle called *Pterostichus vermiculosus*, which is peculiarly characteristic of the North Asiatic tundras and has never been observed in Fennoscandia. Its westerly boundary lies in the district about the River Petschora in northern Russia. It is to this district, therefore, that we must turn in order to realise the conditions which obtained in south-eastern Finland in late-glacial times. The smallness of the associated arctic plant remains indicates great severity of conditions, while the thickness of the bed in which they occur seems to point to the persistence of the arctic climate through a fairly long period.

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[1] Harald Lindberg, "Phytopaläontologische Beobachtungen als Belege für postglaziale Klimaschwankungen in Finnland," *ibid.* p. 177.

Climatic optimum in Finland.

The first trees to enter Finland as the climate ameliorated were the birch (*Betula alba*) and fir (*Pinus sylvestris*). These appear to have arrived together, for no beds containing birch alone, such as have been found above the arctic bed in other countries, are known in Finland. They were for a long time the only prevailing forest trees. Towards the end of their period of dominance (the Birch-Fir Period) the climatic conditions had considerably ameliorated, for in the upper portions of the Birch-Fir zone such warmth-requiring plants as *Trapa natans*, *Carex pseudocyperus* and *Ceratophyllum demersum* already made their appearance in localities far north of their present northerly limits. There is thus distinct evidence of a climatic optimum such as has been proved in Scandinavia.

In the zones next above those of the Birch-Fir Period the Spruce or Red Pine (*Picea excelsa*) and a number of other trees, including the oak, alder, ash, plane and lime made their appearance. The southern species, such as *Trapa natans*, which entered at the end of the preceding period, persisted into this.

Finally, the present day shows a marked impoverishment in the flora of the country, and affords ground for assuming a corresponding deterioration of the climate.

Immigration of the Danish flora.

In Denmark evidence of an arctic climate in late-glacial times was brought forward at an early date by Steenstrup and Nathorst (1871), *Salix polaris*, *Dryas* and *Betula nana* occurring in the clay beneath the peat-bogs. These beds at the base of the peat are so closely connected with the lowermost wood-bearing layers, that they afford a striking proof of the gradual passage, with regularly rising temperature, from the tundra period, through the early birch and poplar woods, to the period of extensive forests, first composed of fir, and subsequently of oak and then of beech. The order of immigration is thus the same as that in Sweden, Denmark forming, as a matter of fact, the route by which the Swedish flora entered the country.[1]

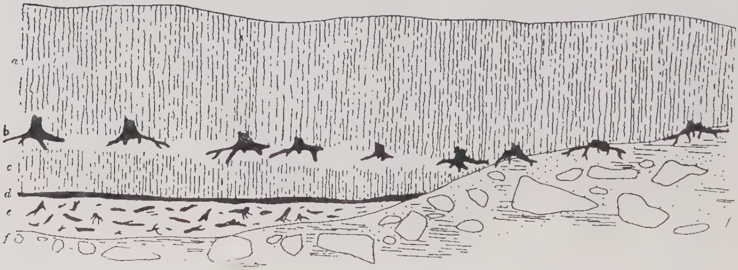

FIG. 155.—Forest and arctic beds at the margin of the deeper peat-layers in the valley between Merrick and Kells Mountains in Southern Scotland. (After Lewis.)

a. Recent peat. *b*. Pine forest. *c*. Eriophorum peat. *d*. Arctic bed.
e. So-called "lower-forest" of birch and alder.

Arctic flora in Britain.

In Great Britain and Ireland a somewhat similar if less complete succession has been established. Remains of arctic plants were first discovered by Bennie,[2] of the Scottish Geological Survey, at the base of lacustrine deposits and peat-bogs, and subsequently by Clement

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[1] V. Nordmann, "Post-glacial Climate Changes in Denmark," *ibid*. p. 313.

[2] Jas. Bennie, "Arctic Plant-beds in Scotland," *Annals of Scottish Natural History*, p. 53. 1896.

Reid,[1] Lamplugh,[2] and F. J. Lewis.[3] Later the birch seems to have arrived, and subsequently the country was overspread with great pine forests, the stools of which are now found in the peat-bogs high up on the hills, and far out in the most exposed portions of the northern and western coasts of Scotland and Ireland. Oak stumps are also found in the peat-bogs, but their relations to the pine forests are not quite clear.

Date of immigration of the pine, oak and hazel.

Now many of the peat-moss forests round the British coasts are deeply submerged, so that we have come to recognise a "Submerged Forest Period" as a distinct epoch in the history of the British Isles. We have shown above (Chap. XVI.) that this period of low sea-level is to be correlated with that of Ancylus times in Scandinavia and Denmark. The pine forests, therefore, reached Britain as they did Sweden in Ancylus times, and we know also, from the sections at Hull (p. 376) and elsewhere, that the oak and hazel also entered the country before this period of low sea-level came to an end.

Westward extension of the forests.

The evidence in the British Isles is therefore, as far as it goes, quite in agreement with that of the continent. It is difficult, however, to cite any clear botanical evidence from this country of the post-glacial climatic optimum so apparent in the north of Europe. Moreover, the mere fact that vigorous pine forests once flourished on the exposed western coasts and islands not only of this country, but also of Norway, tempts one to take quite a different view as to the cause of the wider distribution of the forests than that hinted at above which assigns them to the climatic optimum. The absence of forests in these districts at the present day is not a matter of temperature, but of exposure to the Atlantic winds, and perhaps also of the proximity of the sea. Now if, as seems probable, large portions of the continental shelf were exposed during the Submerged Forest or Ancylus

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[1] Clement Reid, *The History of the British Flora.*

[2] G. W. Lamplugh, *Geology of the Isle of Man*, Mem. Geol. Survey, U.K.

[3] F. J. Lewis, "The Plant Remains in the Scottish Peat-mosses," *Trans. Roy. Soc. Edinburgh*, vol. xli. part iii. No. 28; vol. xlv. part i. No. 2; vol. xlv. part ii. No. 13; and vol. xlvii. part iv. No. 26.

Period, this alone might introduce conditions suitable to the wider distribution of the trees towards the west. It does not, however, follow in the least that their farther extension northward and up the slopes of the mountains was synchronous with this. It may well have occurred during the climatic optimum which at any rate must be invoked to account for the other facts.

Cause of the climatic optimum.

Now the climatic optimum coincided in the main with Littorina time, during which a great part of north-western Europe lay considerably lower than at present, and the sea occupied large tracts of what is now dry land. To this wider extent of the sea the amelioration of the climate has frequently been ascribed. The peninsula of Jutland was at that time under water, and the warm Atlantic currents had freer access to the Cattegat. It is interesting in this connexion to note that Brögger has proved that the climatic optimum is markedly reflected in the Tapes banks of the Christiania region, several of the species being at present relegated to regions much farther south in the neighbourhood of the English Channel. An interesting piece of evidence is afforded by the finding of the West Indian bean, *Entada scandens*, at the base of a peat-bog on the west coast of Sweden. Specimens of this bean are frequently drifted ashore along the coasts of Ireland, Scotland, and Norway, having floated across the Atlantic on the Gulf Stream. It is a significant fact that in Littorina times they should have penetrated as far east as the Cattegat.

The freer access in this manner of the warm Atlantic currents must undoubtedly have had an effect on the climate of south-eastern Sweden. Whether it could affect northern Scandinavia and Finland is quite another matter. The advocates of the theory, however, maintain that the considerably greater area which the Baltic then possessed, combined with the freer circulation in it of warm salt water from the Atlantic, may have produced the effect. There remain, however, two points which do not seem to be explained by this theory. The first is that the climatic optimum seems to have been already reached towards the end of Ancylus time at a period when the Baltic at any rate was cut off from the sea. The second is that Praeger seems to have proved that the marine fauna of Belfast Lough during Littorina time (25-foot or Neolithic Raised Beach) was a somewhat more southerly one than occupies the Lough at the present day. Now it is inconceivable that the very small change of level, amounting to some 18 or 20 feet, which affected the north of Ireland at that period could in any way have influenced the climate of the country.

It would seem, therefore, as if some more fundamental cause must be sought for the change of climate which appears to be proved by comparison of the present and former distribution of plants and animals.

CHAPTER XX

CONCLUSION

Attempts at correlation—America and Europe—Europe and the British Isles—Northern Europe and the Alps—The loess—Speculations as to the causes leading to its formation—Coincidence of the present and pre-glacial sea-levels—Low sea-level during the Glacial Period—Its effect on the Mediterranean—The Straits of Gibraltar—Precipitation as a factor in glaciation—Unsatisfactoriness of the theories.

In the present state of our knowledge the correlation of the glacial stages in different countries is entirely a matter of speculation. No doubt, in the future, means will be found to effect these correlations. The outlook in the domain of archaeology is especially hopeful, and the very exact researches which are now being carried on in this subject, promise in the near future to make clear the relation between the North European and Alpine glaciations. Whether a result of this nature will ever be obtained in the case of Europe and North America is more doubtful. In the meanwhile little good is done by the drawing up of general correlation tables, in which an apparently satisfactory result is often obtained by ignoring difficulties.

Comparison of the American and European drift-sheets.

There are, however, certain points of resemblance between the American and European drift-sheets, which point to the probability of the ice-sheets which deposited them having been contemporaneous and subjected to the same climatic influences. In both there is an outer, relatively featureless area of drift, for the most part highly denuded, and an inner area with pronounced topography and relatively negligible denudation. The inner area is in both cases limited by a very remarkable moraine, and there are other concentric moraines marking further stages of retreat. The outer areas beyond the great moraines seem in both countries to be further subdivisible into older and newer sheets. For purposes of comparison the series may be written down in parallel columns thus:

AMERICA.	EUROPE.
Wisconsin Drift-Sheet.	Drift of the Baltic Glacier.
Great Kettle Moraine.	Great Baltic Moraine.
Iowan Drift-Sheet.	The Newer extra-morainic Drift.
Illinoian and Kansan Drift-Sheets.	The Older extra-morainic Drift.

Bipartition.

A further striking point of resemblance is the apparent bipartition of both series. In America, between the Wisconsin and older drift occurs the Toronto formation of Coleman (p. 170), and the interglacial deposits described by Leverett as Peorian (p. 169). The existence of an interglacial period, indicated by these deposits, is confirmed by the double rise of Lakes Bonneville and Lahontan (p. 196). In Europe, between the drift of the Baltic Glacier and the older drift, occur the Eemian deposits recently brought into prominence by Madsen, Nordmann and Hartz[1] (see p. 125). There is, therefore, in this respect a certain similarity in the glacial succession in the two countries, and a further correspondence is noticeable in the relation of the loess to the older drift-sheets on both sides of the Atlantic.

Comparison of Great Britain and the Continent.

Strange as it may seem, even the correlation of the British glaciation with that of the continent of Europe presents considerable difficulty. A certain starting-point is afforded by the isostatic phenomena, for which the tentative correlation suggested in the following scheme is at least a plausible one:

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[1] It should be noted in this respect that Eemian shells have been found in the drift a little outside even the outermost known fringe of the Baltic moraine. It is not necessary, however, to regard the moraine as absolutely limiting the drift of this period.

Scandinavia.	Great Britain.
Yoldia Sea.	Late Glacial (100-foot) Beach.
Ancylus Lake.	Submerged Forest Period.
Littorina Sea.	"Neolithic" (25-foot) Beach.

That the Littorina-Tapes submergence of Scandinavia is the equivalent of the 25-foot beach of Scotland is clear from the fact that both are contemporaneous with the Campignien or Nöstvet Period which preceded the Neolithic proper. The fauna, moreover, indicates that both occurred during the post-glacial climatic optimum. The Ancylus Lake, requiring as it does a period of low sea-level for the laying dry of the Sound and Belts, must clearly be regarded as having existed in the Submerged Forest Period. The fauna of the Yoldia Sea is distinctly arctic. So is that of the 100-foot beach of Scotland. Both appear to have been contemporaneous with the later stages of the glaciation. Thus far all seems clear, but when we look more closely into the question difficulties crop up. The Yoldia Sea came into existence during the retreat of the ice from the Baltic Moraine. We must therefore consider what is the equivalent of the Baltic Moraine in Great Britain. Certainly not the Cleveland-York Moraine, which lies near the limit of the newer drift, for at this stage the Scandinavian ice occupied the basin of the North Sea. There is no sign of any halt in the retreat between this and the Morainic Glaciation of the Highlands of Scotland. The latter must, therefore, be regarded as the probable equivalent of the Baltic Moraine. This is what introduces the difficulty, for the maximum of the Yoldia Sea is later than the Baltic Moraine, while the 100-foot beach of Scotland certainly did not overlast and probably preceded the greatest extension of the Highland Moraine Glaciation (see p. 370). A possible explanation of this discrepancy may be supplied by extending the theory of Chapter XVIII., and supposing that in consequence of the relatively small load on the Scottish Highlands, isostatic recovery set in and reached its maximum rate of progress somewhat earlier than in Scandinavia. The state of equilibrium between the rising land and the rising ocean, which we have conceived to have occurred at the Yoldia maximum (see p. 419), thus happened at an earlier date in Scotland, during the maximum, and not during the retreat of the Highland Moraine Glaciation.

The question naturally arises next as to what is the British equivalent of the Eemian Period of the continent, and here it is best frankly to confess that we do not know, and so leave the matter as it stands. It is desirable, however, that this difficulty in the above correlation should be clearly realised.

Comparison of the Alps and Northern Europe.

Finally, in regard to the correlation of the Alpine glaciation with that of northern Europe there is still considerable difficulty. A tentative starting-point is given by the relation to the loess. This is absent from the deposits of the Würm Glaciation, and also from the newer extra-morainic drift of the north. Regarding these as equivalent, we may write down the different stages in parallel columns as follows :—

NORTHERN EUROPE.	ALPS.
Older loess-covered and denuded drift.	Günz- Mindel- and Riss-Glaciations.
Younger loess-free drift.	Würm Glaciation.
Baltic Moraine.	Bühl-stadium.
Ra-moraines and Salpausselkä.	Geschnitz-stadium.
? Epiglacial or other moraines of the Christiania Valley.	Daun-stadium.

This correlation is, however, almost a pure speculation, and is open to the objection that it, like the British succession, finds no place for the Eemian Period.

The Loess.

Possible connexion between glaciation and drought.

The relation between the loess and the glaciation, on which emphasis has been repeatedly laid in the preceding chapters, is one of the most curious phenomena of the Ice Age. The loess is essentially a dry climate formation, and it does not at first sight seem probable that there could be any connexion between drought and glaciation. Recent investigations of the meteorology of the great ice-sheets of the present day seem to show, however, that such a connexion may possibly exist. Both in Greenland and in the Antarctic continent the atmospheric conditions over the inland ice are almost continuously anticyclonic. As a result, along the margin, dry and sometimes even warm foehn-like radial winds predominate, and the precipitation is never very great. This has been proved by the meteorological records of the Antarctic and Greenland expeditions. Nansen has described the occurrence of dust storms on the coast of Greenland. It is possible that the very powerful anticyclones, which must have existed over the American and European ice-sheets, may have extended their influence sufficiently far beyond the margin of the ice to lead to the formation of loess in the surrounding regions. It is conceivable also that the lowness of the sea-level during the Glacial Period, which has been shown above (Chap. XVIII.) to be indicated by certain facts, and also to be probable on *a priori* grounds, may have had an effect in making the climate more continental in character. This last-mentioned cause, however, can hardly have been of more than subsidiary importance, since the westward extension of Europe as a result of the lowering of sea-level was limited by the margin of the Atlantic shelf. Moreover, a very strong objection can be urged against regarding the loess as a marginal product of the glacial anticyclones. It has been pointed out in Chapter X. that the steppe districts of Quaternary times were merely an extension of those of the present day, and that this extension obtained in northern China, where there was no ice-sheet, to an even greater extent than in Europe and North America. We must, therefore, seek for some more general cause for the wider distribution of steppe climates during the Quaternary than is afforded by either of the above-mentioned agencies.

The loess-formation coincident with on-coming glaciation.

It is of the greatest importance in connexion with the question of the origin of the loess to take into consideration Penck's more recent views on the subject. He emphasises the fact that the loess frequently contains a fauna of arcto-alpine character, and must therefore be regarded as in part at least contemporaneous with an Ice Age. Now there is a fair amount of evidence (see p. 141) tending to show that the Alpine region was occupied by an arctic fauna at two different periods which were separated from one another by a temperate period. The older arctic fauna was Moustérien in age and belonged to the Riss Ice Age, the younger was Aurignacien, Solutréen, and Magdalénien, and belonged to the Würm Ice Age. Now the greater part of the loess is Aurignacio-Solutréen, and therefore its arctic fauna must be that of the Würm Ice Age. The formation of the loess, however, did not overlast the Würm maximum. It is clear, therefore, that the agencies which led to its deposition were in operation during the oncoming of the Würm Glaciation. How far their action extended back into the preceding Riss-Würm Interglacial Period is not known. Penck insists that the available evidence shows that the Interglacial Period was in the main characterised by the widespread distribution of woodland round about the Alps, and that the steppe phase succeeded the woodland phase. If, then, as he seems to think, the formation of loess is a concomitant of oncoming glaciation, the matter is placed in an entirely new aspect, and, until further researches throw some light on the subject, the less said about it the better.

Significance of the return to the pre-glacial sea-level.

Let us now turn to the consideration of a fact the importance of which in glacial geology can hardly be overestimated. Throughout the southern half of the British Isles and the north of France the level of the sea in pre-glacial times was practically the same as that of the present day. It would seem as if in this area there was a normal level to which the sea returned after the very considerable oscillations which it underwent during and after the Ice Age. Now these oscillations, as has been pointed out in Chapter XVIII., were very probably due to the binding up of great quantities of water in the Quaternary ice-sheets. Other things being equal, the sea-level on this theory would give a rough idea of the extent of the glaciers existing on the globe at any period. Now in view of the fact that the area of distribution of the above-mentioned pre-glacial beach is, as far as we can see, a stable one, and has not been affected by folding or faulting in Quaternary times, it is not so wild a speculation as it might otherwise seem, to take the coincidence of present and pre-glacial levels as indicating that the extent of the ice-sheets during the formation of the pre-glacial shore-platform was much the same as at the present day.

Of course no one would be so foolish as to claim anything in the nature of proof for a proposition of this kind. Its sole value is that it affords a sort of basis for further discussion of the subject, and gives colour to the working hypothesis, so widely adopted by geologists at the present day, that the Ice Age was an interruption of the normal sequence of climatic evolution. Even in the present state of our knowledge we are in possession of many facts curiously at variance with this idea of a return to normal conditions. In Scotland, for instance, there is a pre-glacial shore-line a little over 100 feet above the present level. In Norway there is also a pre-glacial platform of marine erosion at levels varying from 100 to 400 feet above sea-level.[1] In Spitzbergen what appears to be the same plain of marine erosion occurs at a height of 250 feet. If for the moment we make the rather dangerous assumption that all these shore-lines are contemporaneous with the pre-glacial beach of southern Britain, we find ourselves presented with the very curious anomaly that in the isostatically depressed areas the pre-glacial shore-line lies at higher levels than in the outlying regions where no results of glacial depression are apparent.

The Mediterranean basin during the Ice Age.

The condition of the Mediterranean Basin during the Ice Age forms an interesting subject for speculation. It has been suggested that it was at this period a region of interior drainage unconnected with the ocean, and this supposition is in agreement with certain facts referred to in preceding chapters (see pp. 149, 249). On *a priori* grounds this result might be deduced from the general lowering of sea-level during the Ice Age (see p. 413), provided this lowering was sufficiently great to lay bare the sill of the Straits of Gibraltar. This is, of course, a very considerable lowering, but it is not outside the range of possibility. The evaporation from the surface of the Mediterranean at the present day more than counterbalances the supply by the tributary rivers, with the result that the flow of water in the Straits is on the whole from without inwards, and the water of the Mediterranean is salter than that of the ocean. It is clear that, if the connexion were at any time severed, the level of the lake thus formed must necessarily have sunk until equilibrium was re-established. It has been supposed that two lakes came into existence, one a fresh-water lake, in the eastern depression, which drained into the other in the western depression. It is interesting to think what must have happened when the ocean level rose once more as a result of the dissipation of the ice-sheets, and its waters began to pour over into the empty basin. The inflow, small at first, must have ultimately increased to enormous dimensions, as the channel was slowly lowered by erosion and the ocean level slowly rose. If there were any unconsolidated materials on the sill of the Strait, the result must have been a genuine debacle, and, if we consider the length of time which even an enormous torrent would take to fill such a basin as that of the Mediterranean, we must conclude that this result was likely to have been attained in any case. Now this may seem all the wildest speculation, but it is not entirely so, for, if we examine a submarine contour map of the Straits of Gibraltar, we find there is an enormous valley running up from the Mediterranean deep, right through the Straits, and trenching some distance out on to the Atlantic shelf. This valley or gorge is probably the work of the inflowing waters of the ocean at the termination of the period of interior drainage.

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[1] Hans Reusch, "Strandfladen, et nyt traek i Norges geografi," *Norges Geol. Undersögelse,* No. 14, Aarbog for 1892 og '93, Christiania, 1894. Fridtjof Nansen, *The Norwegian North Polar Expedition,* 1893-1896, *Scientific Results,* vol. iv. p. 51 (1904), where further references are given.

Precipitation as a factor in glaciation.

There has of recent years, been a tendency among geologists to exaggerate the importance of precipitation in the production of glaciers and ice-sheets. It is clear that, in the case of a range of mountains which rises above the snow-line, an increase in the precipitation may easily cause a growth of the snow-fields and glaciers, but such a change could never give rise to the formation of glaciers in low mountain ranges such as those, for example, in the south and west of Ireland. These ranges, however, undoubtedly possessed powerful, more or less independent ice-caps during the Ice Age, so that it is obvious that to look for the origin of the British Ice-sheets in an increase of precipitation alone is absurd. If, however, the snow-line were so far lowered that the higher portions of these mountain ranges rose above it, then there is little doubt that, with the copious precipitation which obtains at present, they would at once begin to nourish glaciers. The really essential thing is the lowering of the snow-line, so as to bring some portion of the range into the region of perpetual snow. Then, and not till then, might an increase of precipitation have its effect on the growth of glaciers.

This nevertheless does not make the matter perfectly clear, for the height of the snow-line, although mainly a matter of temperature, is, to a certain extent, dependent on precipitation. Thus, in the west of the Alps, and in the extreme south-east, near the Adriatic, where the precipitation is greatest, the present snow-line is relatively depressed. To a certain small extent, therefore, it might be possible for an increase of precipitation to bring the snow-line down on to a range of hills, the summits of which, with the lesser precipitation, lay just below it. The higher summits of the Scottish Highlands, for instance, just fail to reach the snow-line, and small patches of snow generally persist throughout the summer in the sheltered corries on Ben Nevis. Were it not that the precipitation on these hills is already enormous, one might possibly conceive that an increase of it might lead to the growth of these snow patches. However, in cases like this, where a large proportion of the increase is bound to fall as warm rain, any gain in the direction of glaciation is more than doubtful.

Moreover, as Penck justly remarks, in the case of a mountain range like the Alps, where the precipitation varies from place to place, any increase of precipitation must have been greatest where the present precipitation is greatest, and the snow-line ought to have been depressed in these localities more than elsewhere. But he has shown (see p. 144) that the snow-line of the Würm Ice Age was parallel to that of the present day. We are therefore forced to the conclusion that the main factor in glaciation is lowering of temperature, and that variations in precipitation, though liable to lead to local complications, can in no sense be regarded as a primary cause.

It must be admitted that, among the theories that have been brought forward to account for the phenomena of the Ice Age, there is not a single one which meets the facts of the case in such a manner as to inspire confidence. An almost fatal objection to Croll's famous theory is the date it assigns to the end of the Ice Age, which it places some 80,000 years back. If, as De Geer seems to have clearly established (see p. 343), the ice-margin retreated north past Stockholm only about 9000 years ago, this practically excludes any possibility of a connexion between glaciation and changes in the eccentricity of the earth's orbit.

Of all the light that has been thrown upon Quaternary geology of recent years by far the most illuminating and inspiring is this investigation by De Geer of the chronological and thermographic record afforded by the late-glacial laminated clays of Sweden. These promise to yield on closer examination a complete climatic record and an exact measure of the whole time which has elapsed during and since the northward retreat of the ice-margin. If similar records can be discovered in other parts of the world, a most potent means of correlation and a test of the world-wide nature of climatic oscillation is at last in our hands. " When," says Gilbert, in the introduction to his monograph on Lake Bonneville, " the work of the geologist is finished and his final comprehensive report written, the longest and most important chapter will be upon the latest and shortest of the geologic periods." This daily becomes more obvious, as the record is slowly deciphered and new vistas of knowledge are opened up to our eyes. We have in the history of the Quaternary Period a region of research, full of hope and of the most romantic interest, promising not only to reveal the events which accompanied and influenced the evolution of man, but to afford an outpost from which we can look back into the ages which preceded his advent upon the earth.

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